REPORT METEOROLOGY AND CLIMATOLOGY No. 121, 2025

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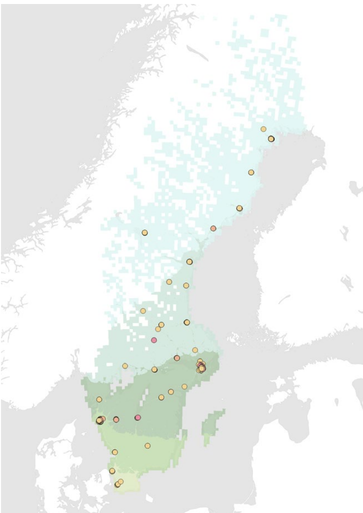

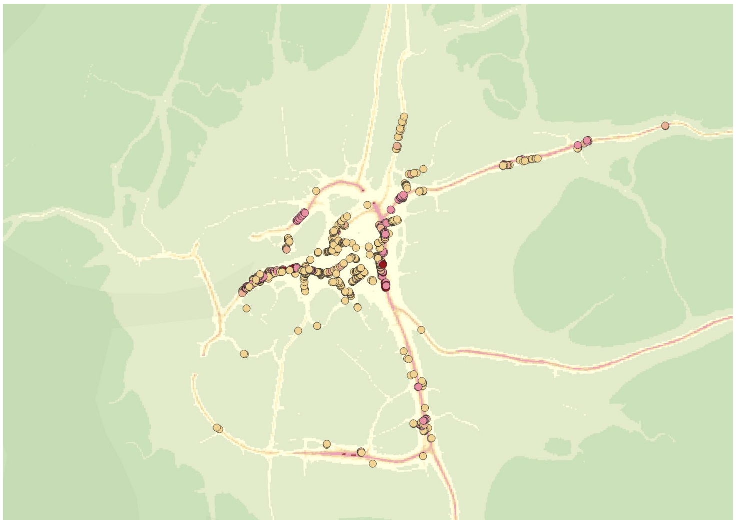

Cover page figure:
Annual mean concentrations of PM_{10} over Sweden and zoomed in over Gothenburg for 2023.

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Summary

In 2024, SMHI published modelled national high-resolution concentrations of NO_2, PM_{10} and $PM_{2.5}$ for the year 2019. The simulations were performed using a new methodology that enabled a combination of dispersion modelling on regional, urban and street scales without double counting of emissions. With a spatial resolution as high as 50x50 m^2, these results provided the most detailed description of air quality over Sweden so far.

Using the same methodology, we have now performed national simulations for the year 2023. Whereas the first project focused on developing a framework for model calculations, the aim of this project has been to further improve the model quality by improving emissions and modelling assumptions, as well as optimising calculation performance. In addition to evaluating concentrations related to the current Swedish air quality standards, we have also included the limits from the updated EU Ambient Air Quality Directive (AAQD) and the World Health Organization (WHO) guidelines.

The emissions and model improvements include:

- Better handling of street level NO_x chemistry.
- Improved emissions data from the public power and industrial sectors as well as for the domestic and international shipping sectors.
- Traffic emissions data has been improved by regionalising vehicle fleets, the assumptions regarding street gritting and the date interval for changing to/from winter tyres.

The model results have been validated against applicable Swedish measurement stations and show:

- Significantly reduced NO_2 concentrations for traffic stations compared to measurements due to model improvements. The modelled concentrations now tend towards underestimation, but with improvements in quality compared to the 2019 results.
- Improved quality of PM_{10} concentrations compared to measurements due to a number of improvements to the emission assumptions. The quality has improved particularly in northern Sweden due to regionalised assumptions regarding use of winter tyres and street gritting with sand.
- Similarly high quality of $PM_{2.5}$ concentrations as that of the 2019 results.

Overall the validation shows improved results, but still with some exceedances with regards to the RDE and RPE and/or through the MQI statistical indicators. More work is needed to improve the model quality enough for it to pass all the data quality objectives for the whole country. It is therefore important to note that more detailed local scale studies are needed to fully understand the air quality at a given location.

Generally, the highest concentrations are seen in urban environments and along major roads. The traffic sector is one of the dominating source sectors as can now also be seen in the source apportionment, a new feature implemented in this upgraded version of our modelling system.

The results from this study are meant to be used by Swedish municipalities and other organisations to help analyse and improve their assessment and mitigation of local air quality. The results have been made freely available on the SMHI web portal “Luftwebb”.

Sammanfattning

2024 publicerade SMHI högupplösta modellerade halter av NO_2, PM_{10} och $PM_{2,5}$ över hela Sverige för år 2019. I projektet togs en ny modelleringsmetodik fram för att kombinera spridningsberäkningar på tre skalor; regional, urban och gaturum, utan dubbelräkning av emissioner. Med en rumslig upplösning på 50x50 m^2 så var dessa resultat den hittills mest detaljerade beskrivningen av luftkvaliteten över hela Sverige.

Genom att använda samma metodik har vi nu också utfört nationella beräkningar för år 2023. Där det första projektets fokus låg på modellutveckling så har fokus i det här projektet varit att fortsatt förbättra modellen och emissionsbeskrivningen samt optimering av beräkningskedjan. Förutom att utvärdera de resulterande halterna till dagens svenska miljökvalitetsnormer så har vi även utvärderat halterna mot gränsvärdena från det kommande uppdaterade EU-direktivet om luftkvalitet och renare luft i Europa samt från riktlinjerna från WHO (Världshälsoorganisationen).

Förbättringar som har gjorts kring emissioner och modeller inkluderar:

- Bättre hantering av gaturumsbidragets NO_x-kemi.
- Emissioner har förbättrats för uppvärmnings- och industrisektorerna samt för inrikes- och utrikessjöfartssektorerna.
- Trafikemissioner har förbättrats genom regionaliserade antaganden för fordonsflottor, dubbdäcksanvändning och sandning.

Modellresultaten har validerats mot tillgängliga svenska mätstationer och visar:

- Signifikant reducerade halter av NO_2 jämfört med mätvärden. Dessa minskningar beror huvudsakligen på modellförbättringar och tenderar nu att understiga mätvärdena. Modellkvaliteten är dock tydligt förbättrad jämfört med de tidigare resultaten för 2019.
- Förbättrad kvalitet på halterna av PM_{10} jämfört med mätvärden, främst på grund av ett antal förbättrade modelleringsantaganden. Kvaliteten har höjts mest i norra delarna av landet genom regionaliserade antaganden kring dubbdäcksanvändning och sandning.
- Samma höga kvalitet på halterna av PM2,5 jämfört med de tidigare resultaten för 2019.

Generellt visar valideringen förbättrade resultat, men det finns fortfarande överskridanden jämfört med kvalitetsmålen RDE och RPE och/eller MQI. Ytterligare arbete kommer att behövas för att förbättra modellkvaliteten tillräckligt för att alla kvalitetsmål ska klaras för hela landet. Det är därför viktigt att påpeka att mer detaljerade lokalskaliga beräkningar behövs för att helt förstå luftkvaliteten vid varje given plats.

De högsta halterna ses oftast i städerna eller intill större vägar. Trafiksektorn är en av de viktigaste källorna, något som nu också kan ses i källfördelningen som är en ny funktionalitet i webbtjänsten.

Resultaten ifrån denna studie är ämnade att användas av svenska kommuner och andra organisationer för att hjälpa analysen och förbättra luftkvalitetsarbetet. Dessa resultat har gjorts fritt tillgängliga på SMHIs webbportal ”Luftwebb”.

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1 Introduction

The SMHI project for modelling of high-resolution concentrations of NO_2, PM_{10} and $PM_{2.5}$ for all of Sweden was initiated to reach a better, unified understanding of the air quality situation over the whole country. This data was published for the meteorological year 2019 by Grundström et al. (2023).

In this project we have used methodology from the previous study to produce data for the meteorological year 2023. This project also includes a number of improvements to emissions data, model assumptions and validation methodology. In addition to evaluating concentrations related to the current Swedish standards, we have also included and evaluated the limit values from the updated EU Ambient Air Quality Directive (AAQD, 2024/2881) and the World Health Organization (WHO) Guidelines updated in 2021.

The new AAQD was formally adopted by EU in autumn 2024 and comes with major amendments to the previous directives 2004/107/EC and 2008/50/EC. These new regulations are scheduled to be adopted by the EU member states by the end of 2026, with regulations that are to be legally binding by 1 January 2030. One major aspect of the new AAQD is significantly more ambitious air quality standards that are now closer to the WHO guidelines for NO_2, PM_{10} and $PM_{2.5}$. These values are presented for the yearly averages in Table 1, and are also presented and discussed in more detail in the result sections.

Pollutant	**NO_2**	**PM_{10}**	**$PM_{2.5}$**
Current AAQD			
Air quality standard[1] (yearly average)	40	40	25
Air quality objective[2] (yearly average)	20	15	10
2030 AAQD			
Air quality standard	20	20	10
Air quality objective	10	15	5
WHO guideline			
WHO guideline[3] (yearly average)	10	15	5

Table 1. Limit values for the current and 2030 air quality standards, air quality objectives and WHO guidelines for annual means of NO_2, PM_{10} and $PM_{2.5}$ (unit µg/m³).

[1] The Swedish air quality standards: https://www.naturvardsverket.se/globalassets/vagledning/luft-och-klimat/mkn-utomhusluft/sammanstallning-miljokvalitetsnormer.pdf

[2] The Swedish environmental quality objectives for clean air: https://www.naturvardsverket.se/en/environmental-work/environmental-objectives/clean-air/

[3] WHO global air quality guidelines: https://apps.who.int/iris/bitstream/handle/10665/345329/9789240034228-eng.pdf?sequence=1&isAllowed=y

Other aspects related to the new AAQD are increased demands related to monitoring of air quality as well as a larger focus on modelling. These include a demand for national simulations like this study. When measured concentrations exceed the limit values, models will be needed to give a geographical description of the exceedance, show dominating sources and show that the planned measures will lead to sufficient reductions in concentrations. Modelling is also expected to be used to give better information for the placement of measurement stations. Models also have to be more accurate (with high resolution in both time and space) and follow new, stricter, quality control procedures.

In Sweden, only a few measurement stations showed exceedances of the new limit values for NO_2 for year 2023. With NO_x emissions expected to be further reduced in the coming years, primarily from an increased share of electric vehicles, the risk of exceedances by 2030 is expected to be low. For $PM_{2.5}$, the year 2023 had no exceedances of the new limit values and was close to following the even stricter WHO guidelines. PM_{10} is thought to be the most problematic pollutant with regards to the new limit values. In 2023, 21 measurement stations had exceedances of the new limit values and, in contrast to NO_2, particle emissions are not expected to decrease significantly going forward. It is therefore expected that significant effort will be needed to sufficiently reduce PM_{10} concentrations in both large cities and smaller towns.

The work and results described in this study can play an important role in the air quality work going forward. With its high spatial resolution and high level of detail, this data gives a nationwide description of the air quality situation today. The resulting concentrations also include source apportionment, so that every coordinate has a description of the contribution from each emission sector.

In section 2, we describe the dispersion model methodology and emission descriptions along with improvements done since the previous project. In section 3, we show the results from the validation work and in section 4, we discuss the results from the national modelling. Finally, in section 5, we include some general discussions around the results and discuss what work could come next.

2 Methodology

The dispersion calculations in this study follow the same modelling chain as Grundström et al. (2023). In this methodology, described schematically in Figure 1, different dispersion models are used on regional and urban scales, coupled together with a third model for the street canyon contribution where applicable. The results are hour-by-hour high resolution concentrations of NO_2, $PM_{2.5}$ and PM_{10} for the year 2023, covering all of Sweden. These models depend on input data such as emissions, traffic, physiography, building geometries and meteorology. The modelled concentrations are also adjusted using observations, both on a regional and urban scale.

In this section, we give a brief description of the methodology along with notable improvements made to the input data and models.

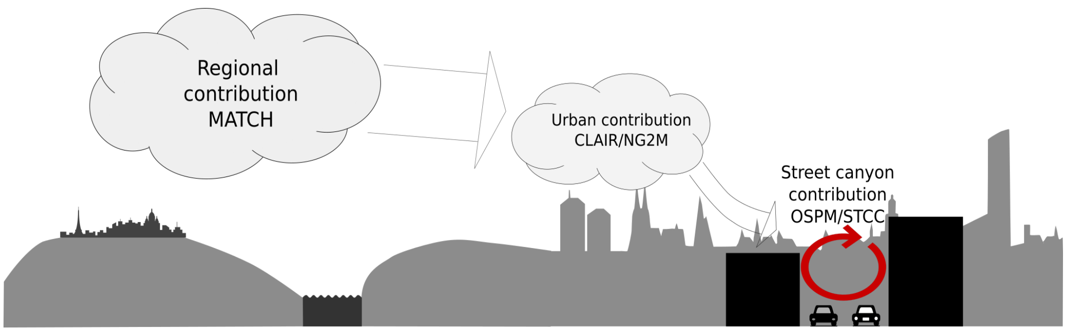

Figure 1. Parts involved in the calculation of air pollution concentrations down to street canyon level for all of Sweden.

2.1 Emission data

The base emission data sets used in this project are gridded Swedish emissions of NO_2, $PM_{2.5}$, PM_{10} and O_3 extracted from the SMED[4] database at a resolution of 1x1 km^2 for the latest available year (2021). Emissions for the rest of Europe come from EMEP[5] (0.1 degree resolution) for the year 2021, along with daily forest fire emission data from the CAMS Global Fire Assimilation System (CAMS-GFAS).

Further improvements to the Swedish data set include improvements to the geographical distribution of small-scale residential heating (described in Grundström et al. 2023), industry and energy point sources (described in section 2.1.1) as well as domestic and international shipping (described in section 2.1.2). The different emission sectors are defined according to the GNFR activity categories[6] which are presented in Table 2.

Table 2. GNFR emission sectors and descriptions.

GNFR	Description
A: PublicPower	Emissions from public electricity and heat production
B: Industry	Emissions from industrial combustion plants
C: Other Stationary Comb	Emissions from small combustion plants
D: Fugitive	Fugitive emissions
E: Solvents	Emissions from the use of solvents
F: Road Transport	Emissions from road transport
G: Shipping	Emissions from domestic shipping
H: Aviation	Emissions from landing and take-off, for domestic and international flights
I: Offroad	Emissions from offroad mobility, such as machinery used in industry, households, agriculture, railways and fishing
J: Waste	Emissions associated with waste handling (except combustion for energy)
K: Agri Livestock	Emissions associated with livestock and manure management
L: Agri Other	All other agricultural emissions, such as fertilizer, crops and field management
M: Other	Other anthropogenic sources
N: Natural	Emissions from natural sources, such as forest fires
O: Avi Cruise	Emissions from the cruise phase of both domestic and international flights
P: Int Shipping	Emissions from international shipping

[4] Geographically distributed emission data from SMED (submission 2023, emission year 2021): https://www.smhi.se/data/miljo/nationella-emissionsdatabasen

[5] EMEP emission database (emission year 2021): https://www.ceip.at/webdab-emission-database

[6] GNFR activity codes: https://www.ceip.at/fileadmin/inhalte/ceip/1_reporting_guidelines2014/annex_i_rev18-11.xlsx

2.1.1 Improvements to energy and industry point sources

The available SMED emissions for energy and industry sources (GNFR A and B) have a spatial resolution of 1x1 km^2 with zero, or close to zero, information on point sources in the later submissions. This is a critical weakness for the purpose of air quality modelling, as the position and physical attributes of each smokestack can have a great effect on the local air quality.

To improve the emission data we have, therefore, used Utsläpp i siffror[7] (UTIS) by Naturvårdsverket to convert the gridded emission data to point source data for roughly 300 of the largest Swedish point sources. In this conversion, we have moved the emissions from each industry from the emission grid to a dedicated point source. Each point source includes size of emissions along with physical attributes, such as smokestack dimensions and dimensions of the closest buildings, that have been estimated using images of each site. The remaining emissions are still considered grid emissions according to the SMED data.

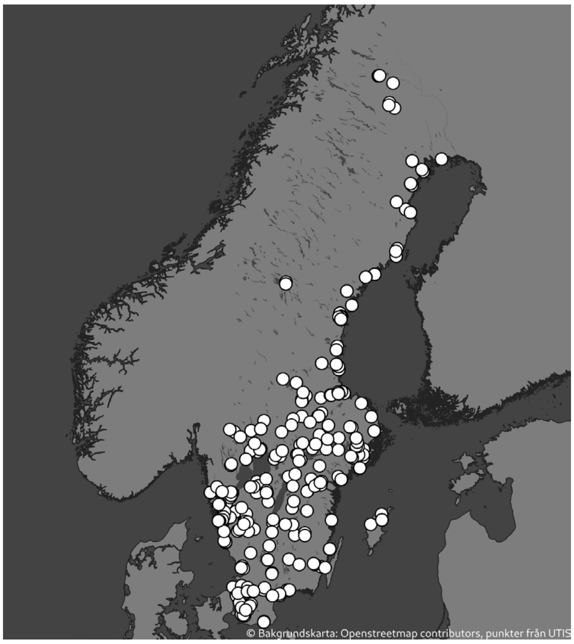

Figure 2. The energy and industry emissions converted into point sources, from data by UTIS.

2.1.2 Improvements to domestic and international shipping

The SMED emissions for domestic and international shipping (GNFR G and P) have a spatial resolution of 1x1 km^2. In the current SMED methodology they are produced in multiple, separate steps: bottom-up calculations of the national fuel usage, emission factors from large-scale statistics and geographical distributions using a separate bottom-up calculation. This methodology leads to significant uncertainties in the shipping sector for the purpose of air quality modelling.

To better understand the effects of shipping, we have therefore used the SMHI Shipair system to calculate emissions for both shipping sectors at a higher spatial resolution of 100x100 m^2 for emission year 2023. We have also calculated two sets of general time variations for near-coast shipping and for shipping at sea.

Shipair is a bottom-up emission model that is used in a number of the steps for the calculation of the official SMED emissions. It is based on AIS data (Automatic Identification System) that specifies an identification number along with highly detailed positional data for each ship. This is then combined with technical ship data that describes parameters such as ship type, gross tonnage, main and

[7] https://utslappisiffror.naturvardsverket.se/

auxiliary engines, fuel type and ship age. Combined emissions can then be modelled at a very high level of detail both at sea and in port.

In Figure 3, we show an example of the resulting shipping emissions. The gridded emissions are emitted in the dispersion model using an initial height distribution between 15 and 80 meters.

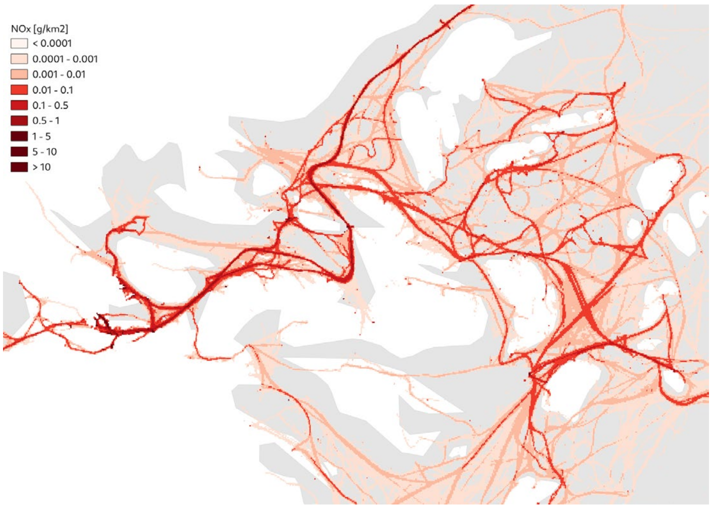

Figure 3. Example of the updated domestic and international shipping emissions of NO_x over parts of the Stockholm archipelago from Shipair for emission year 2023.

2.2 Road traffic data

The road transport sector (GNFR F) is the most important, having emissions that are both high and often located where people live. To obtain a higher spatial resolution than is reported by SMED, emissions from this sector are calculated based on road network vector data delivered to SMHI by the Swedish Transport Administration (Trafikverket).

The road network describes each road link as a vector with a number of attributes both related to the physical properties of the specific road, such as road type and road width, and to the traffic on the specific road, such as the speed limit, annual average daily traffic (AADT) and share of heavy traffic. The traffic data is modelled using a combination of measurements, primarily on the state owned roads, and models related to where people live and work for the other roads.

The road network is then combined with vehicle fleet data for each road type and the corresponding set of emission factors in HBEFA (Handbook Emission Factors for Road Transport), a step done by the Swedish Environmental Institute (IVL). This project has used the latest available HBEFA version 4.2, which was originally released in 2022.

We have also made a number of improvements to various aspects of the road traffic data described in the following sections.

2.2.1 Improved national traffic data

The total traffic volume differs between the road network delivered to SMHI by Trafikverket and the official Swedish statistics delivered to Trafikverket by WSP. This difference stems from different assumptions regarding the traffic on municipal and private roads, where the traffic on the state owned roads is significantly more accurate due to more extensive measurements.

We have therefore scaled the traffic on the road network used in this work to reach the same numbers as the official Swedish statistics. This has led to an increase in traffic of around 30 % on municipal roads and an increase of around 40 % on private roads.

The road network has also been processed by manually removing the most significant tunnels within cities. For the longer tunnels we have assumed ventilation and moved emissions further away from the entrances. For shorter tunnels we have moved the traffic emissions to the entrances. We have also added a small number of missing roads in Malmö and a handful of other cities.

Some municipalities have only recently started to report their traffic measurements to Trafikverket, but this data has so far not been used to calibrate the traffic data delivered to SMHI. As this data is of particular importance for validating the model near air quality measurement stations, we have requested data on annual average daily traffic, and share of heavy vehicles near measurement stations, from some municipalities and found other data sources where these have been made available.

Generally, when comparing these local measurements to the simulated data from Trafikverket, we have found the simulated data to underestimate the traffic found from local measurements. In most cases by a factor of less than 2-3, but in a few cases by factors of up to 40 (a simulated AADT of 200 to a measured AADT of 8000).

2.2.2 Update of the NORTRIP model for modelling of road dust

Emissions from non-exhaust road traffic is the major source of PM emissions from traffic. They are modelled using the NORTRIP model (Denby et al. 2013), where emissions and effects from road wear, suspension, surface dust loading and retention of wear particles are modelled using traffic and meteorological data.

The version used in the previous project was based on a checkout of the official code from 2021. Since then, a number of updates have been made to the model both regarding bug fixes and parameter settings. For this project, the NORTRIP code was updated in October 2024. The update had relatively small effects on the yearly averaged emissions, but resulted in significant changes to the highest emission peaks, both in amplitude and when they occurred.

2.2.3 Regionalised assumptions regarding use of winter tyres and street gritting

Sweden has a wide variation of temperatures and weather situations between the southern and northern parts. This also means a wide variation between different parts of the country in the use of winter tyres (to which degree studded tyres are used, when winter tyres are used) and the amount of street gritting with sand.

In Grundström et al. (2023), different studded tyre usage was included for each trafikverksregion (Trafikverket divides the country into six different regions, “trafikverksregioner”), but no other regionalisation of parameters was done in the NORTRIP model. In this project, we have also implemented regionalised assumptions regarding when summer and winter tyres are used, as well as how much gritting is done during wintry conditions.

We have used the same trafikverksregioner as for the studded tyre usage and grouped them up into three regions, South, Middle and North specified in Table 3.

Parameters	South	Middle	North
Trafikverksregioner	Syd, Öst, Väst, Stockholm	Mitt	Nord
To summer tyres (from/to)	31 Mar/15 Apr	7 apr/30 Apr	15 apr/15 May
To winter tyres (from/to)	1 Oct/1 Dec	1 Oct/1 Dec	1 Oct/1 Dec
Sand gritting [g/m2]	0	250	250
Max interval for gritting with sand	-	7 days	7 days

Table 3. Regionalised NORTRIP parameters.

The information on when summer and winter tyres are changed has been updated based on dialogues with a number of car workshops in northern Sweden. The information on the gritting is based on dialogues with a few municipalities in northern Sweden.

These values tend to be difficult to estimate, and there are likely differences both within and between municipalities as well as vehicles travelling between regions. Gritting is also done in the southern regions, but the degree to which it is utilized and on which road types, is still unknown to us. A wider survey would likely result in different assumptions with a higher spatial resolution.

2.2.4 Regionalised assumptions regarding the vehicle fleet in each municipality

The number of electric and hybrid electric vehicles have been steadily increasing for a number of years. In 2023, there were about 5.9 % electric vehicles, 3.8 % electric hybrids and 5.5 % plug-in hybrid vehicles nation-wide. These vehicles have zero NO_x emissions (when using electricity), but similar particulate matter emissions as the interaction between the tyres and the road are more or less similar.

The numbers given above are the national averages. However, there are large variations between municipalities as shown by the Vehicle statistics[8] data from Transport Analysis (Trafikanalys). The municipalities with the lowest share of electric vehicles are Dorotea and Sorsele, both with a roughly 1 % total share, and the municipalities with the highest share are Solna with a 41 % share and Nacka with a 37 % share.

To reproduce these differences, we have assumed different vehicle fleets for each individual municipality based on the Transport Analysis data. As vehicles travel between municipalities, we have created an average fleet based on the data for each municipality and all its neighbours. The results are shown in Figure 4.

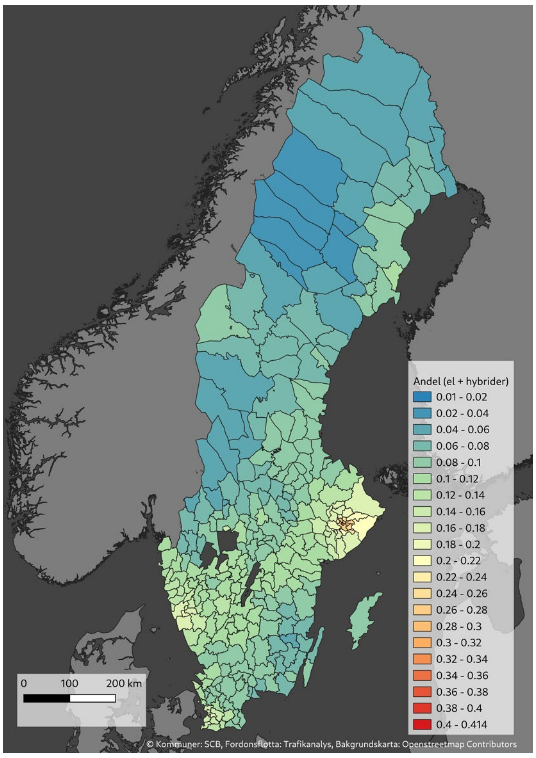

Figure 4. Share of electric vehicles (electric + hybrid) as used in this project, based on data from Transport Analysis for year 2023.

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[8] https://www.trafa.se/en/road-traffic/vehicle-statistics/

2.3 Building data

When modelling the air quality within a street canyon, the ventilation is of critical importance. The two major aspects to the ventilation are the physical dimensions of the surrounding buildings together with the wind flow (direction and speed). A badly ventilated street canyon can trap the air, increasing the concentrations compared to a better ventilated street canyon with otherwise similar road properties.

In the previous project, a national dataset of buildings was created by combining geographic building data from OpenStreetMap (OSM) with laser scanning data ("Laserdata skog") produced by the Land Survey (Lantmäteriet). For each building in OSM, a building height was derived from the 90th percentile of points from the laser data within the building polygon.

However, in the previous study, a couple areas including Örebro län, northern Västergötland and Gotland were still missing laser scanning data that now have been finished by Lantmäteriet. Both data sets have now been updated for all of Sweden, including new buildings and improvements to existing buildings.

2.4 Meteorological data

Meteorological data for year 2023 is used to drive all dispersion models as well as the road dust model NORTRIP. In the regional MATCH model, 3-dimensional meteorological data for all of Europe is taken from the ECMWF weather model HRES[9] (0.1 degree horizontal resolution). For the urban dispersion modeling, the ECMWF data is combined with hourly 2-dimensional data over Sweden from the MESAN[10] model (2.5 km resolution) together with global radiation from STRÅNG[11].

Meteorology is perhaps the strongest driver between year-to-year variations in air quality. High concentrations of air pollution tend to be created during cold and stable weather, whereas wet and windy weather tends to decrease the concentrations.

The meteorological year of 2023 is summarized in Figure 5 for temperature and precipitation as compared to the 30-year period of 1961-1990. Temperatures show relatively warm months of January, February and June and relatively cold months of March, April and July[12]. Warm weather tends to have effects on both ozone and particulate matter. Particularly in the winter months, warm weather tends to decrease the amount of particle emissions from small-scale heating systems. As for precipitation, the southern half of the country was unusually wet, especially during the Spring, which can cause roads to be depleted from particles before they can be suspended in the air.

The combination of temperature and precipitation in the Spring months of 2023 is a likely cause of less intense high particle episodes in this year than compared to 2019.

[9] https://confluence.ecmwf.int/display/FUG/HRES+-+High-Resolution+Forecast

[10] https://www.smhi.se/data/utforskaren-oppna-data/meteorologisk-analysmodell-mesan-api

[11] https://www.smhi.se/forskning/forskningsenheter/atmosfarisk-fjarranalys/strang-en-modell-for-solstralning-1.329

[12] https://www.smhi.se/klimat/klimatet-da-och-nu/arets-vader/aret-2023-mycket-nederbordsrikt-i-sodra-sverige-1.203029

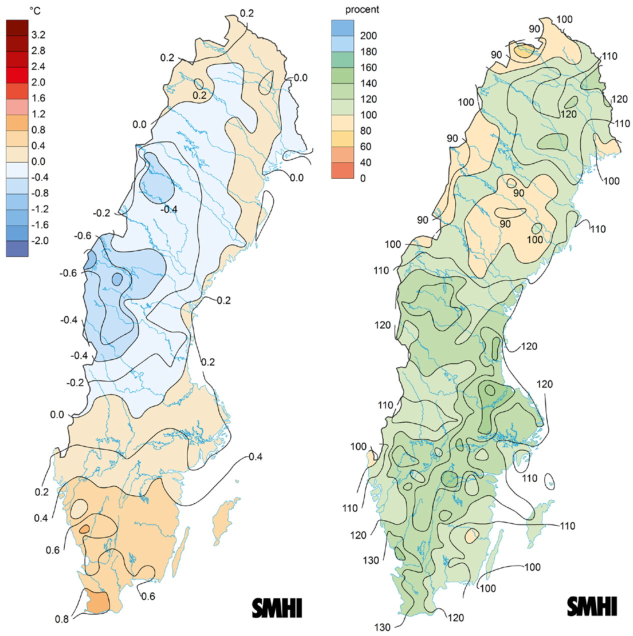

Figure 5. Annual mean deviations in temperature (˚C) and precipitation (percent) from the normal annual mean (mean value of 1961-1990) for 2023.

2.5 Dispersion calculations

The dispersion methodology is based on a combination of dispersion models at regional, urban and street level scales. Transport over longer distances than 15 km is described by the regional dispersion model MATCH (Multi-scale Atmospheric Transport and CHemistry model) (Robertson et al., 1999; Andersson et al., 2007; Andersson et al., 2014) and urban dispersion modelling is described using the Gaussian model NG2M which is run on the CLAIR platform. At street level, we use the street canyon model Operational Street Pollution Model (OSPM) (Bercowitz et al. 1997).

The modelling concept is presented in a schematic diagram in Figure 6, and it is discussed briefly in the following sections. See Grundström et al. (2023) for a more detailed description.

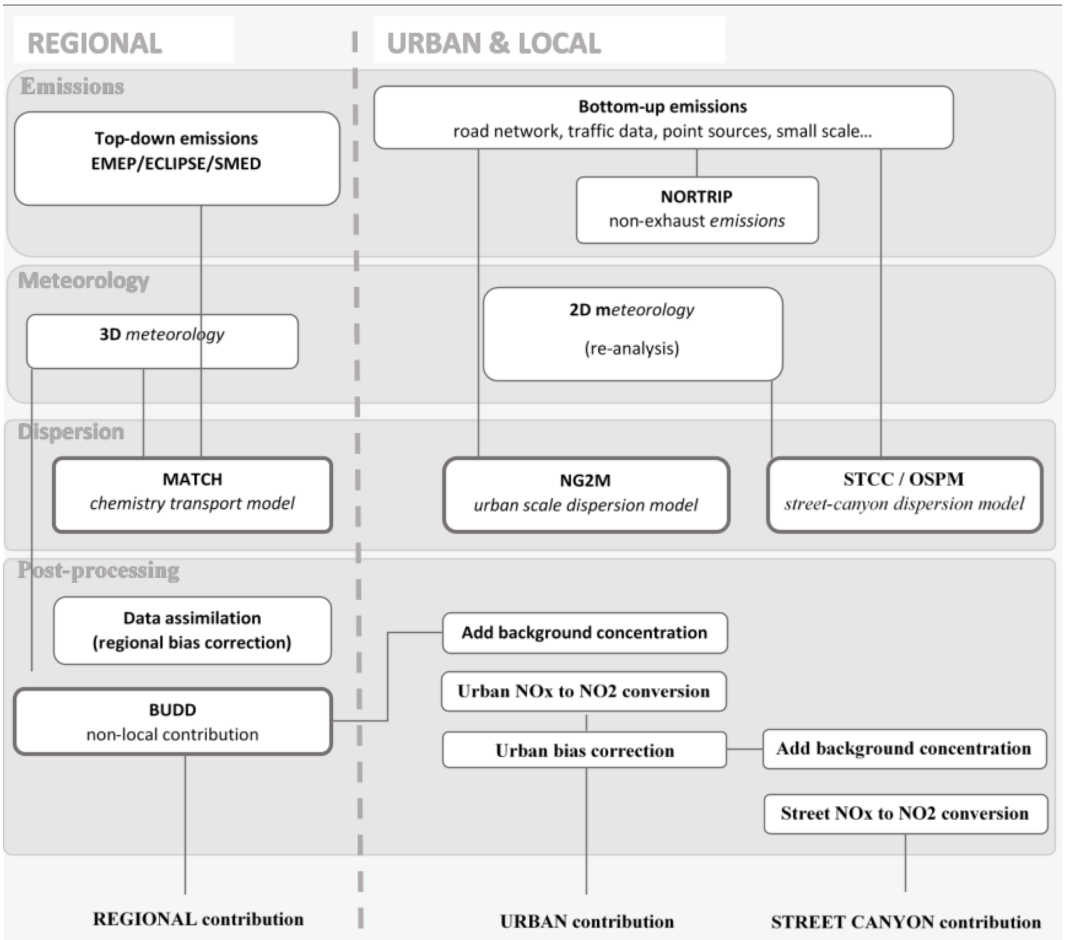

Figure 6. Schematic illustration of the modelling concept used in this study. The modelling consists of three main model chains (columns) for calculating the regional, urban and street canyon contribution which make up the total air pollution concentration. There are several data flows from input data (emissions and meteorology) into the dispersion models (MATCH, NG2M and STCC/OSPM) followed by a number of consecutive steps for post-processing of data (such as bias corrections, NO_2-NO_x-O_3-chemistry). All steps within the CLAIR-system (urban and local) are automated.

2.5.1 Regional scale dispersion modelling

The chemical transport model MATCH has been used to calculate the regional concentrations at a 5 km horizontal resolution. This resolution is obtained using a nested approach, where a first model run is used over all of Europe at a 0.1 degree resolution (approximately 11 km) and a second model run is made at a higher spatial resolution of 5 km over Sweden only. These simulations include emissions from forest fires from CAMS Global Fire Assimilation System (CAMS-GFAS) as well as sea salt contributions to particulate matter. Some particle emission sources are partly or completely missing from the models. These are contributions that are diffuse and difficult to describe, such as dust from agriculture, pollen and other natural sources.

To avoid systematic underestimation of modelled concentrations, a bias-correction is carried out for particles, NO_2 and O_3 using data from hourly and daily regional measurement stations for 2023. The daily bias is calculated at the location of each regional background measurement site, and an interpolation is then carried out hour by hour over Sweden, where the difference between model and measurement is used to adjust the modelled concentration fields.

The post-processing scheme BUDD (Backtrace Upwind Diffuse Downwind, Segersson 2021) is finally applied to the regional concentrations. This removes the urban contributions from the MATCH results, as this contribution is modelled at a higher detail level in the following step.

2.5.2 Urban dispersion modelling

Urban dispersion modelling is done within the CLAIR air quality modelling toolbox. CLAIR integrates various dispersion models on the urban and local scale with emission inventories, emission models and monitoring data for both independent use and within an automated modelling chain.

In this work, the NG2M model is used within the CLAIR platform for dispersion modelling over a set of smaller 'tiles' (10x10 km^2) and then aggregated into a complete national data set following the methodology described in Segersson et al. (2021). Emissions can be described using four different source types in CLAIR; point, line, area and grid sources, with different descriptions of the resulting plume. Grid sources are interpreted as multiple area-sources in NG2M.

This method also provides a source apportionment of the urban concentrations, in which the contributions from five emission sectors are handled separately in the calculations. These sectors are made available in the final results, and include (see Table 1 for information on GNFR sectors):

- Traffic exhaust: GNFR F (exhaust emissions), represented by line sources.
- Traffic non-exhaust: GNFR F (non-exhaust emissions) modelled by NORTRIP, represented by line sources.
- Small-scale residential heating: GNFR C2, represented by gridded sources at 100 m resolution.
- Shipping: GNFR G and P, represented by gridded sources at 100 m resolution.
- Other sources: GNFR A, B, C1, E, H, I, J, K, L, represented by a mixture of gridded emissions and point sources.

Due to the computational expense of the urban calculations, relevant statistical metrics such as yearly means and percentiles are calculated for each tile and species before the full time series are discarded.

2.5.3 Street canyon dispersion modelling

The urban dispersion modelling described above produces results at a very high spatial resolution, but does not consider effects due to reduced ventilation caused by street canyons. Particularly in urban areas with streets with high traffic surrounded by tall buildings, this effect can be a major contributor to the total concentration.

Pollution levels inside these street canyons are therefore calculated using a third model, STCC, which in turn uses the Operational Street Pollution Model (OSPM) (Bercowitz et al. 1997). OSPM requires additional data such as building height, street geometry, traffic count and wind speed. STCC then uses OSPM to calculate concentrations considering two scenarios; both with and without surrounding buildings. The difference between these two scenarios describes the effect from the local street canyon only, which is then added on top of the regional and urban concentrations into a final total concentration. This is done in STCC for all roads with nearby buildings and an AADT > 1000.

During the validation in the previous study, we noted that the modelled NO_2 concentrations tended towards being significantly higher than the measurements, which was a trend that was not seen for the other species. This was true to a smaller degree for the urban contribution and particularly for the street canyon calculations. In this work, we have updated some assumptions in the NO_x chemistry (in which $NO_2 + O_2 \leftrightarrow NO + O_3$) of the street canyon concentrations.

2.5.4 Measures calculated

The calculations include the following measures:

- NO_2: Yearly average, 98th percentile daily, 98th percentile hourly (current EU Directive), 95.1th percentile daily, 99th percentile hourly (EU Directive 2030), 99th percentile daily (WHO).
- PM_{10}: Yearly average, 90th percentile daily (current EU Directive), 95.1th percentile daily (EU Directive 2030), 99th percentile daily (WHO).
- $PM_{2.5}$: Yearly average (current EU Directive), 95.1th percentile daily (EU Directive 2030), 99th percentile daily (WHO).

To ensure sufficient model quality, a validation of model results compared to urban background measurements is then carried out and is presented in section 4.

2.6 Improvements to the computation methodology

In the previous study, the calculations took a total of about seven weeks to finish on the NSC supercomputer. The major part of the computational time was on the urban and street level calculations, and improving these through refactoring and optimization was therefore a big priority. After profiling the calculations of a typical urban tile, these improvements included:

- Further work on the refined grid that started in the previous project, in which methodology was implemented where the resolution of the NG2M grid farther away from emission line sources could be automatically reduced. In this study, we have also included refinement of grid cells farther away from point sources.
- Implementation of a smarter mask for parallelization of the NG2M calculations, in which the computational tiles were categorized into urban and rural tiles that are handled differently. The latter category allowed a larger number of parallelized tasks, as they have significantly fewer emission sources and therefore require less memory each.
- Improvement of the emission calculations as well as postprocessing with calculation of yearly averages and percentiles of each tile.

Combined, this led to significant improvements in calculation times where the total calculation time for the whole model chain was reduced from seven weeks down to about four weeks.

3 Validation

A validation was carried out where model results were compared to urban background measurements as well as local traffic sites. In the final results, a bias correction factor is applied to the urban concentrations, but the validation of the urban stations is performed before this step.

Validation is made both for the current statistical indicators described in section 3.1.1 as well as for the model quality objectives developed by FAIRMODE in section 3.1.2.

3.1 Data quality objectives for air quality modelling

According to Annex 1 in the European Ambient Air Quality Directive (AAQD, 2008/50/EG)[13], the data quality objectives for air quality modelling compared to measurements are defined as ”the maximum deviation of the measured and calculated concentration levels for 90 % of individual monitoring points, over the period considered, by the limit value, without taking into account the timing of the

[13] Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02008L0050-20150918

events." Maximum allowed modelling uncertainties per pollutant and temporal resolution are listed in Table 4.

Modelling uncertainty	**NO_2**	**$PM_{2.5}$ and PM_{10}**
Hourly	50 %	-
Daily	50 %	-
Yearly	30 %	50 %

Table 4. Maximum allowed modelling uncertainty according to the AAQD (2008/50/EG).

3.1.1 RDE and RPE

Two statistical indicators have been defined to assess the modelling quality as defined in the AAQD; Relative Percentile Error (RPE) and Relative Directive Error (RDE). These are defined as:

$RPE = |O_{perc} - M_{perc}|/M_{perc}$

$RDE = |O_{LV} - M_{LV}|/LV$

where O is the observation, M is the modelling result, perc is the relevant percentile (or annual mean value when assessing annual mean) and LV is the limit value in the EU Ambient Air Quality Directive. O_{LV} represents the observation closest to the limit value and M_{LV} the corresponding modelling result.

Two indicators are used because they are suitable for different situations, depending on how close the air pollution concentrations are to the limit values.

The benefit of the RDE indicator is that the model is evaluated focused on the limit value. However, if the hourly or daily concentration levels are far lower than the limit value, which is often the case in Sweden, the RPE indicator is a better choice for percentiles. The RDE would in those cases only evaluate the extreme values. For evaluation of the annual mean values however, RDE is recommended for concentrations well below the limit value, and RPE is preferred for annual mean values that are close to or higher than the limit values[14]. Both RDE and RPE are presented below for all measurement stations.

3.1.2 Modelling quality objective (MQO)

While the indicators RDE and RPE are simple indicators to apply, many factors are not considered with such unrefined measures. Information that is lost includes timing of events between measurement and model, and the fact that the measurement uncertainty differs depending on pollution level. An improved method to assess modelling quality has been developed in the framework of FAIRMODE[15]. The software DELTA tool[16], has been developed to support European air quality modellers in the diagnostics and assessment of air quality modelling performances under the AAQD (European Commission, 2022).

Based on the indicators in DELTA tool, we have developed a standalone code that reproduces the methodology for producing Target diagrams. This methodology compares modelled and measured timeseries data of pollutant concentrations in given locations. A minimum data availability (currently 75 %) is required for statistics to be produced at a given measurement station. Based on this data, a

[14] Swedish Reference laboratory for modelling recommendations (in Swedish): https://www.smhi.se/reflab/kvalitetssakring/kvalitetssakring/kvalitetsmal

[15] FAIRMODE (Forum for Air Quality Modelling in Europe):https://fairmode.jrc.ec.europa.eu/

[16] DELTA tool: https://aqm.jrc.ec.europa.eu/

number of statistical indicators are calculated together with a Model Quality Objective (MQO)[17], defined as the minimum level of quality to be achieved by a model for policy use. The MQO is constructed on the basis of the observation uncertainty.

How well model results compare to measurements at a station, according to the MQO, can be visualized in a Target diagram. If the station is plotted inside the yellow circle (T<1), the MQO is fulfilled. The diagram also provides information about whether the model error is dominated by bias (either negative or positive) or by correlation or standard deviation. MQO must be fulfilled for at least 90% of the available stations.

In the new AAQD[18] that will be legally binding by 2030, the MQO will substitute the current model quality definition with RPE and RDE indicators.

3.2 NO_2

The validation results for NO_2 are divided into validation at urban background sites and at local traffic sites.

3.2.1 Validation at urban background sites

Validation of NO_2 is done against the uncorrected urban background concentrations of ten measurement stations with Malmö Rådhuset as the southernmost station and Falun Östra Falan as the northernmost station. This means that more than half of Sweden is unrepresented by urban background measurements. This is problematic for modelling purposes, as it means that it becomes difficult to determine whether differences between model results and measurements come from the urban background or from only the nearest roads where the site is located.

There is also an uncertainty in the validation of DOAS stations (Differential Optical Absorption Spectroscopy), which is the method for half of the urban background stations. In this methodology, the concentrations are measured as the average along a line of sight of around 100 meters. This is currently not supported in the model; thus, model values are extracted only from a single point along the line of sight which causes some uncertainties in the validation of these stations.

As seen in Figure 7, there is a significant underestimation of the yearly average for two of the stations and overestimation for one station. Appendix 42 includes a comparison between measurements and model for the different percentiles. The model generally underestimates the percentiles while overestimations can be seen at Helsingborg Norr and Stockholm Torkel Knutssongatan. Note that in the national simulations, the urban concentrations at each site and its surroundings are corrected using the measurements.

[17] FAIRMODE guidance document on modelling quality objectives and benchmarking (version 3.3): https://data.europa.eu/doi/10.2760/41988

[18] Proposal for a revision of the Ambient Air Quality Directives:

https://environment.ec.europa.eu/publications/revision-eu-ambient-air-quality-legislation_en

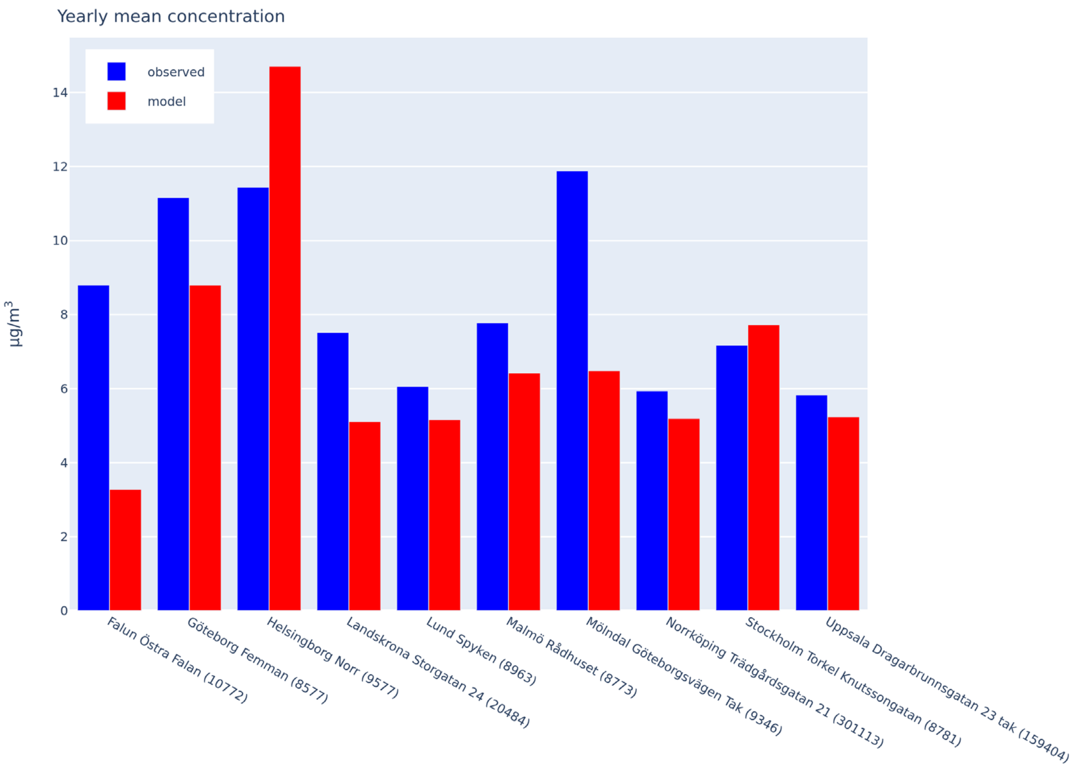

Figure 7. Observed and uncorrected modelled annual mean of NO_2 at urban background sites. Modelled results include a regional and urban contribution. Measurement stations with lower data coverage than 75% have been excluded.

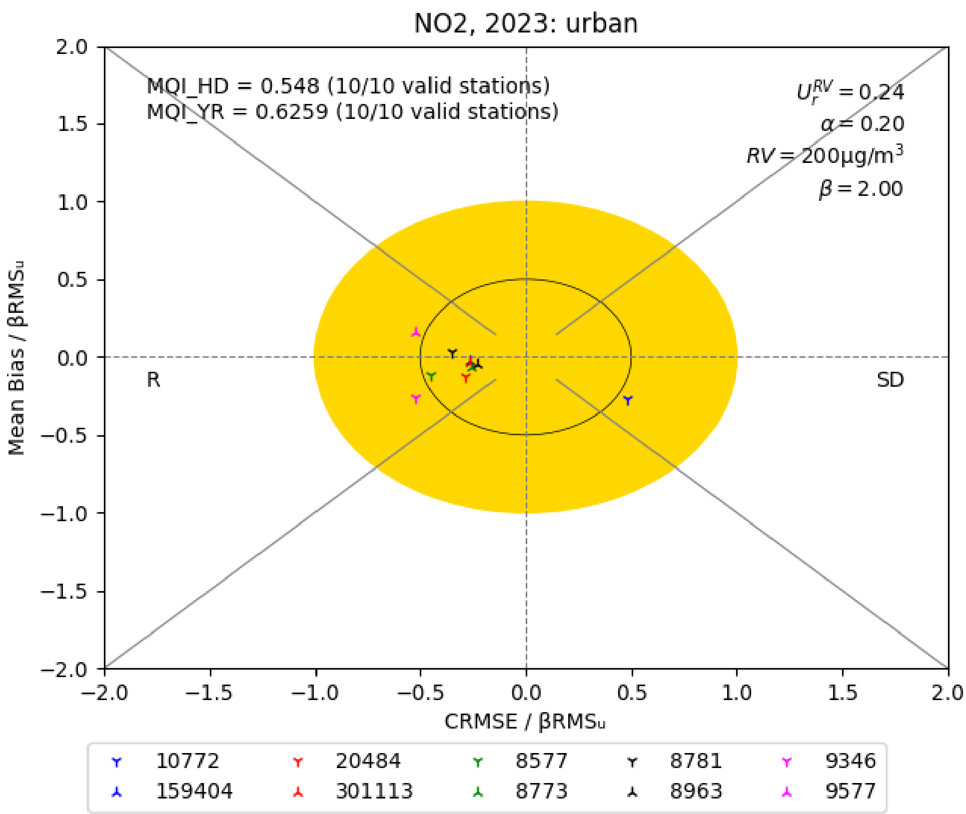

Figure 8. Target plot for NO_2 at urban background sites with hourly time resolution data, without urban correction.

Figure 8 shows the Target diagram for the urban background stations. There were ten stations available with hourly data and a minimum data availability of 75 %. The MQO is passed for all of the stations. The quality objective is thus met for more than 90 % of the stations and the modelling system is of sufficient quality according to the validation method recommended by FAIRMODE.

The indicators RDE and RPE are calculated for the NO_2 annual mean and the hourly and daily 98th percentile, and presented for urban background stations in Appendix A. As the concentration levels are low, the RDE for the annual mean is considered the best indicator. Model results pass the annual mean quality objective, which is less than 0.3 (30 %), for all stations. Quality objectives with less than 0.5 (50 %) are fulfilled for all stations but one. Falun Östra Falan consistently exceeds this level with values of 0.6 or larger, and generally has large differences between measurements and model values that can also be seen for the yearly averages in Figure 7.

3.2.2 Validation at local traffic sites

The validation at local traffic sites is made against 36 measurement stations. A few stations have been excluded from this validation due to poor placement for modelling purposes or poor data coverage.

As is the case for the urban background stations, a significant number of the stations use the DOAS measurement methodology which is not represented perfectly in the current model setup, but these are still included in the assessment.

In Figure 10, we show the yearly averages for all of the stations. We see a trend towards underestimation of the concentrations compared to the measurements, but with a number of stations with really good results (e.g. Göteborg, Malmö, Luleå, Norrköping and most of the stations in Stockholm). This is a big change from the model results of 2019 that instead showed a general overestimation of concentrations. This can be attributed to the many improvements that have been done in this upgraded model version, particularly with regards to updated assumptions in the NO_x chemistry and the vehicle fleet in each municipality.

Appendix 7B includes a comparison between measurements and modelled results for the different percentiles of the traffic stations. Again, there is a tendency for underestimations by the model which can sometimes be significant. There are also examples of relatively good agreement, often but not limited to stations in the Stockholm area. One station, Helsingborg Drottninggatan, shows overestimations throughout for all extreme values. Differences between model and observations generally become more noticeable for extreme values and modelling. This is the case because the most extreme values tend to occur at specific conditions which themselves are difficult to reproduce (such as stable weather conditions).

Generally, observed yearly averages at traffic sites have decreased significantly compared to 2019, and the same trend can be seen in the modelled levels. This is most likely due to changes in meteorology between the two years as well as a rapid electrification of the vehicle fleet in Sweden.

Large underestimations can be observed for some sites (e.g. Botkyrka, Karlstad, Piteå, Trelleborg, Skellefteå, Örnsköldsvik, Östersund). There is no obvious common factor between the sites that explains this. Botkyrka and Trelleborg are relatively open and well ventilated traffic sites. Piteå, Örnsköldsvik and Östersund are quite narrow and confined street canyons. At some sites, these underestimations are likely caused by underestimated traffic volumes or poorly described emissions from other sources, but this is clearly not the case everywhere and the underestimations will need to be evaluated further.

Appendix 7B includes daily averaged time series for a selection of sites. Many of the time series give examples that, for a majority of sites, show how peaks and depressions are well captured by the model even though for some sites the magnitude differs. This shows that the model is well able to accurately capture the temporal variation of NO_2 levels, which is a result of temporal variation in both emissions and weather conditions.

The seasonal variation in NO_2 levels are also well captured for several sites with higher concentration levels during winter. This seasonal behaviour is clear at traffic sites in northern parts of Sweden where winters are cold, while in southern Sweden winters are milder and show a somewhat less dramatic difference in NO_2 between summer and winter peaks. Some sites may be located in valleys of hilly terrain and show this seasonal pattern quite clearly (e.g. Borås, Skellefteå, Falun). Again, the magnitude of some of these winter peaks are not always captured by the model in winter which can be explained by the difficulty in reproducing inversion events that lead to accumulation of pollution levels near the ground.

Figure 9 shows the Target diagram for the local traffic stations. There were 36 stations available with hourly data and a minimum data availability of 75 %, and the MQO is passed for all of the stations. The quality objective is thus met for more than 90 % of the stations and the modelling system is of sufficient quality according to the validation method recommended by FAIRMODE.

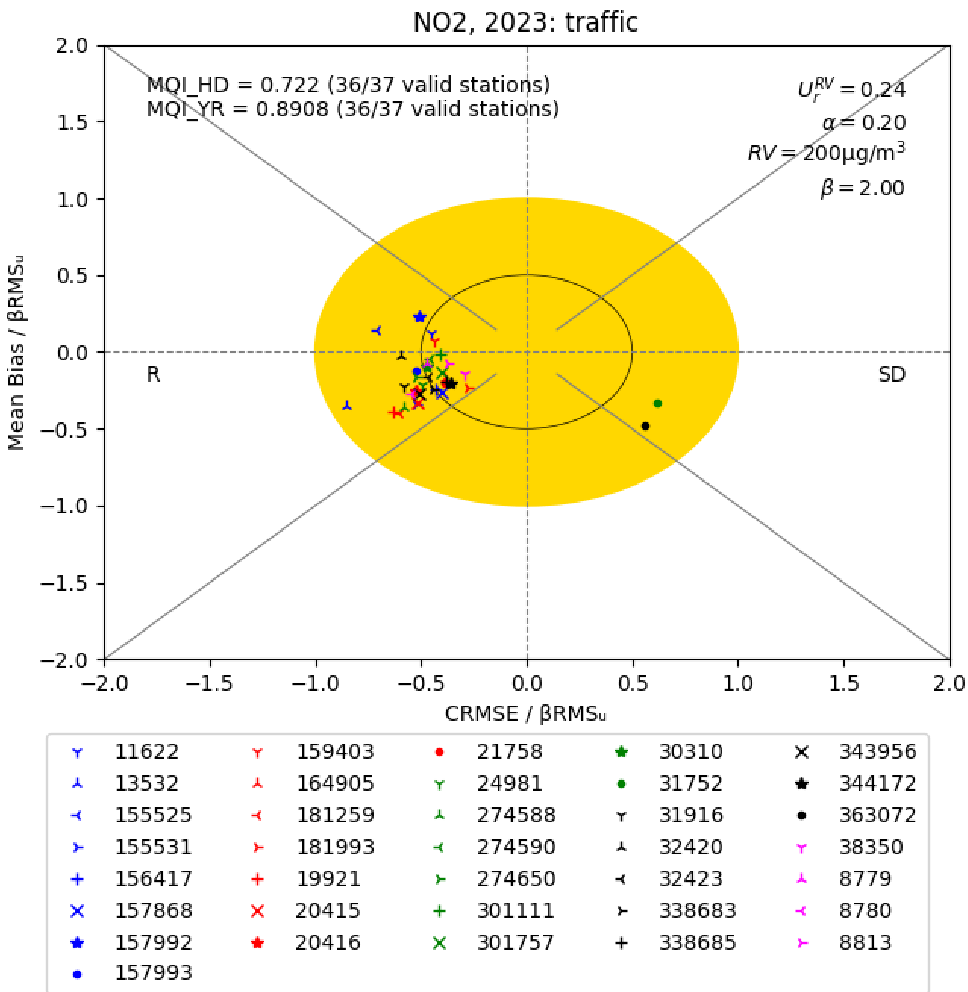

Figure 9. Target plot for NO_2 at local traffic sites with hourly time resolution data, with urban correction applied.

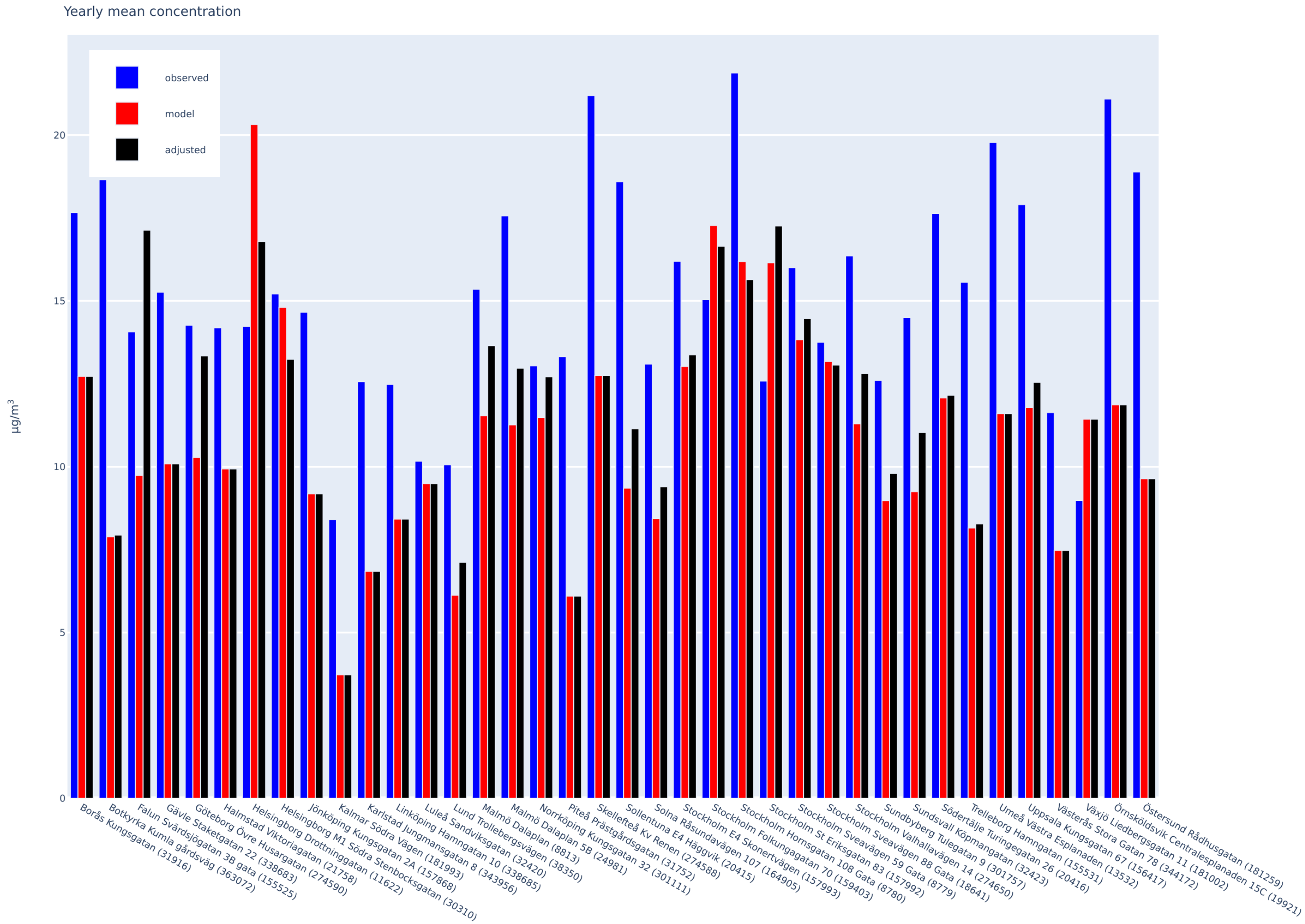

Figure 10. Yearly mean concentrations of NO_2 at traffic sites. Red bars signify modelled values without urban correction. Black bars signify modelled values including urban correction. Total model concentrations in street canyons include regional, urban and street canyon contributions. A majority of the stations are located within street canyons surrounded by buildings. Measurement stations with lower data coverage than 75% have been excluded.

The indicators RDE and RPE for the NO_2 annual mean and the hourly and daily 98th percentile at traffic stations are presented for each station in Appendix B. Model results pass the annual mean quality objective, which is less than 0.3 (30 %), for all 36 stations. For the other quality objectives, 6-8 stations or about a fifth of all stations show RPE and RDE values exceeding 0.5 (50 %).

3.3 PM10

The validation results for PM_{10} are divided into validation at urban background sites and at local traffic sites.

3.3.1 Validation at urban background sites

Validation of PM_{10} is made against the uncorrected urban background concentrations of eight measurement stations from Malmö Rådhuset as the southernmost station to Uppsala Dragarbrunnsgatan as the northernmost station. There is notably one northern station, Sollefteå Torggatan, that was excluded due to low data coverage. The northern half of the country is therefore completely unrepresented for PM_{10}.

As seen in Figure 11, the model produces very good results for all stations that have been modelled with only smaller differences in annual mean concentrations between measurements and model. The largest underestimations are in Göteborg Femman and Jönköping Lantmätaregränd with differences of approximately 2 µg/m^3. Slight overestimations are seen in Norrköping and Uppsala, so there is no overall trend in under or over-estimations. The results for the percentiles are all presented in Appendix 7C and show a generally good agreement, with the exception of Jönköping and Visby.

Figure 12 shows the Target plot for the urban background stations, where 6 out of 7 stations are available with enough data coverage. There are however only 6 stations available on an hourly resolution. The figure shows that the model errors are dominated by low correlation, a common problem when modelling PM_{10}, but all stations are well within the MQO.

The indicators RDE and RPE for the PM_{10} annual mean as well as for the daily 90th percentile are presented for each station in Appendix 7C. As the concentration levels are low, the RDE for the annual mean is considered the best indicator. Model results pass the annual mean quality objective as all stations show RDE values well below 0.5 (50 %) (0.04 is the highest value). For the daily 90th percentile, no thresholds exist, but all but one of the stations have very low RPE and RDE values. The station that stands out is Visby Brömsebroväg with an RDE of 0.59, but the RPE value is on the other hand low.

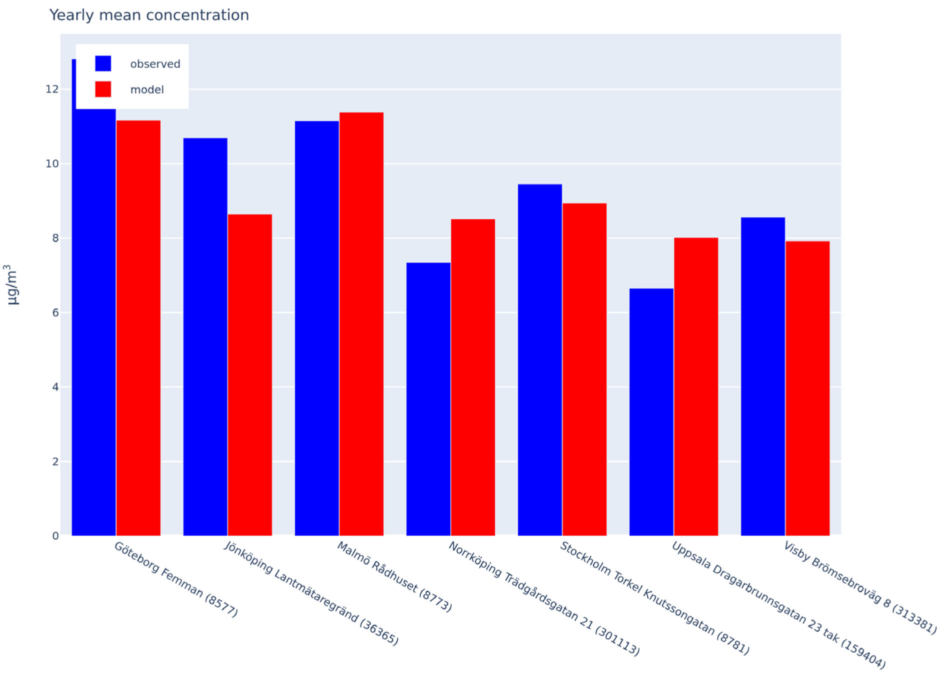

Figure 11. Observed and uncorrected modelled annual mean of PM_{10} at urban background sites. Modelled results include a regional and urban contribution. Measurement stations with lower data coverage than 75% have been excluded.

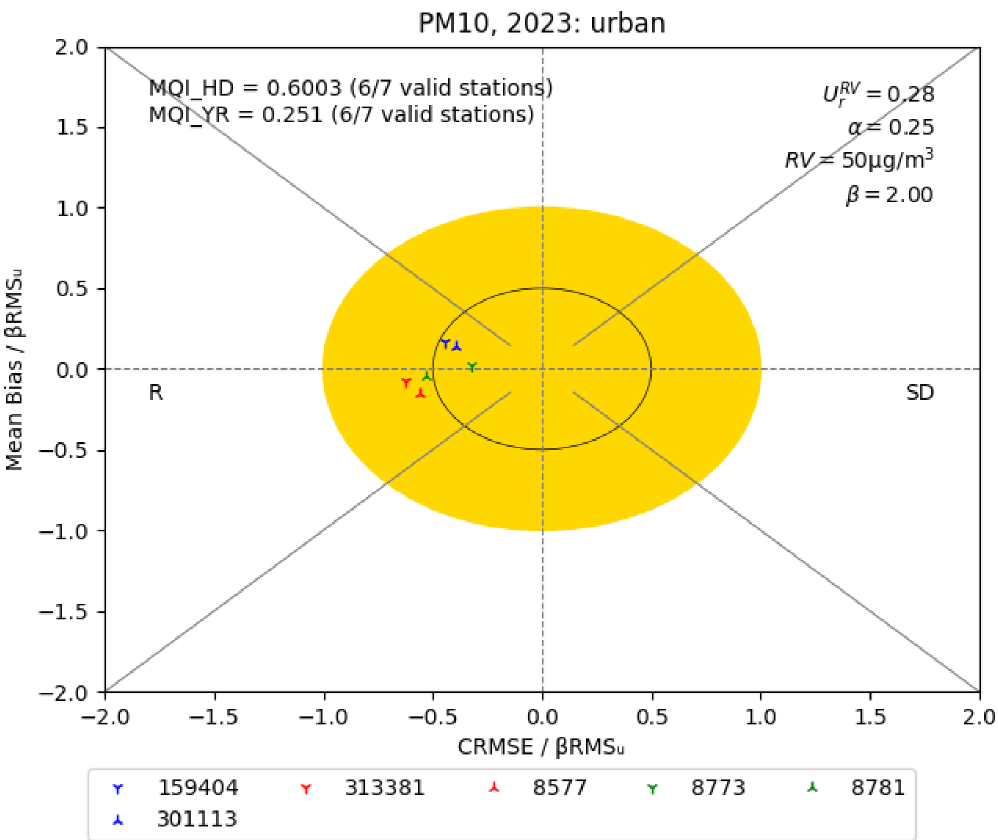

Figure 12. Target plot for PM_{10} at urban background sites with hourly time resolution data, without urban correction.

3.3.2 Validation at local traffic sites

Figure 13, yearly mean concentrations are shown for all of the stations. The results show a varied but overall good result.

PM_{10}

The results for the percentiles are all presented in Appendix 7D and show a trend of general underestimations but sometimes also overestimations. Regarding the WHO guideline several local traffic measurement sites exceed the limit value of 45 µg/m^3, while the model shows fewer sites with exceedances. One site shows exceedances of the current daily air quality standard of 50 µg/m^3 for observations while the model does not indicate this. Additionally, the model indicates an exceedance for the Umeå site, while the measurements do not.

One possible source of overestimates is bad knowledge of the use of dust binding. We have in these models assumed no use of dust binding agents, but doing a better mapping of this along with better estimates of gritting with sand will likely have large effects.

7D shows a subset of daily averaged time series for nine selected sites with both good and poor agreement between measurements and model. In these figures, a clear seasonality can be observed with high concentrations during late winter and early spring months. This is true especially for the northern sites, where traffic with

Figure 14

The indicators RDE and RPE are calculated for the PM_{10} annual mean at traffic stations and as shown in Appendix D. Model results pass the quality objective for the annual mean where all stations show RDE below 0.5. For the daily percentile no model quality objective exists, however 81 - 90 % of the stations show RDE and RPE below 0.5.

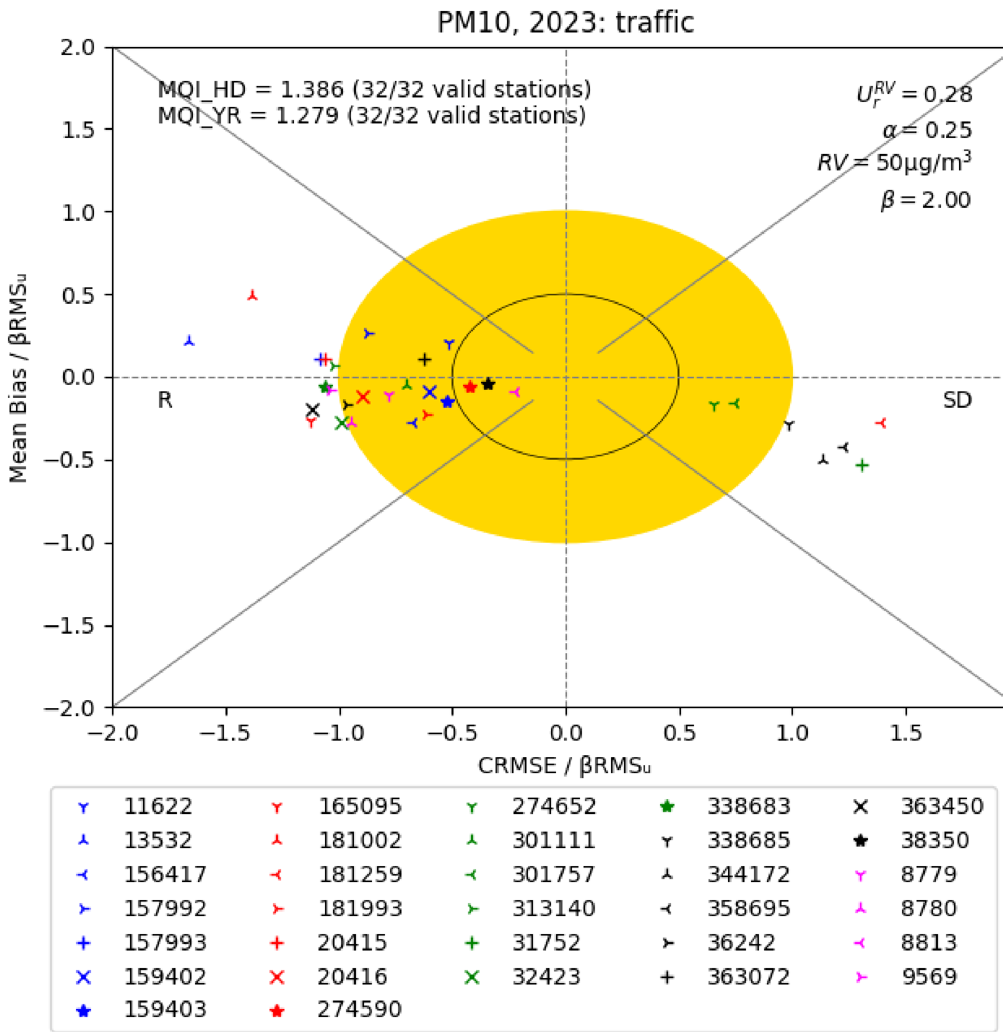

Figure 13. Target plot for PM_{10} at local traffic sites with hourly time resolution data.

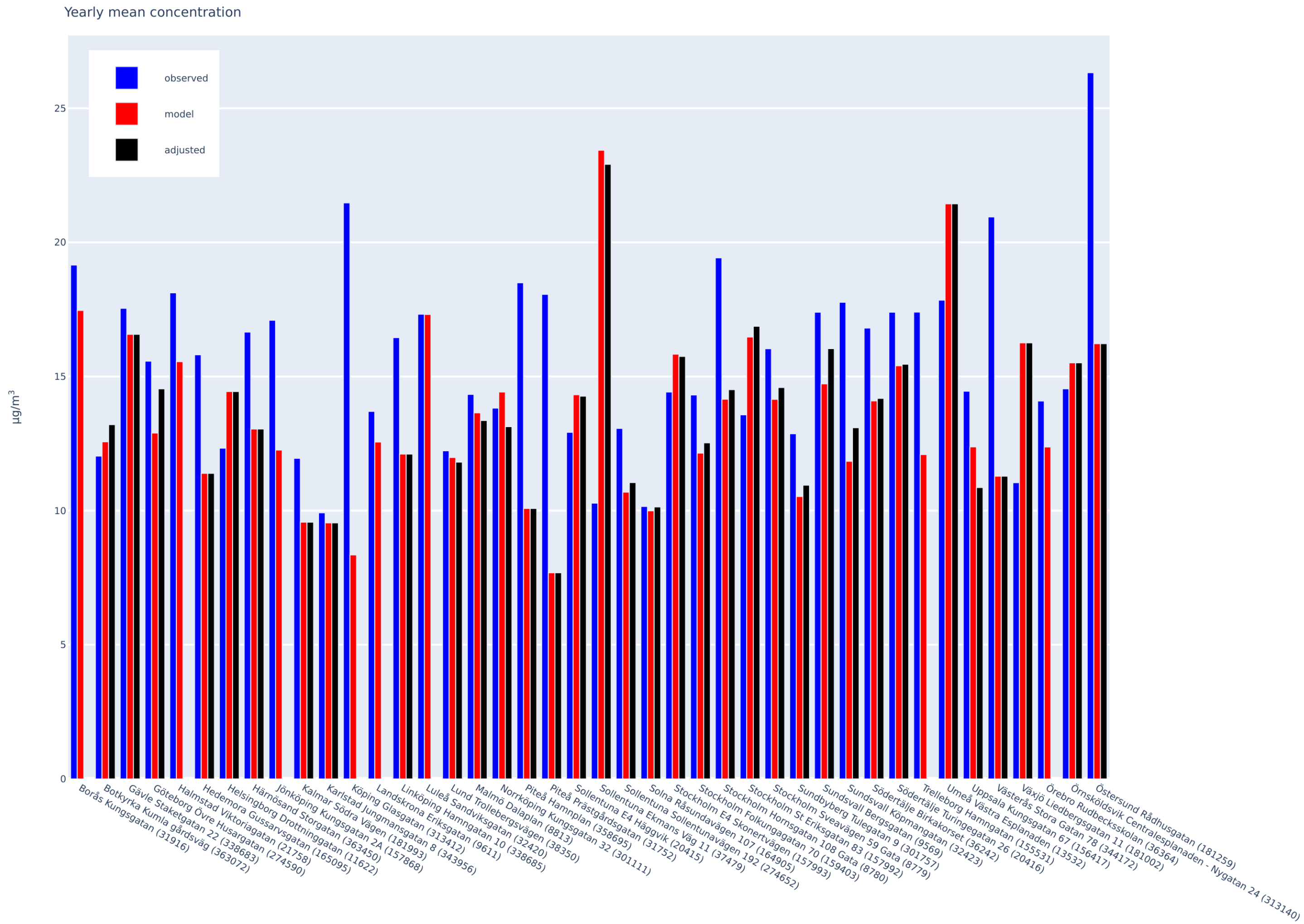

Figure 14. Yearly mean concentrations of PM_{10} at traffic sites with both hourly and daily time resolution data. Red bars signify modelled values without correction of the urban contribution. Black bars signify modelled values including urban correction. Total model concentrations in street canyons include regional, urban and street canyon contributions. A majority of the stations are located within street canyons surrounded by buildings.

3.4 PM$_{2.5}$

The validation results for PM$_{2.5}$ are divided into validation at urban background sites and at local traffic sites.

3.4.1 Validation at urban background sites

Validation of PM$_{2.5}$ is made against the uncorrected background concentrations of eight measurement stations from Malmö Rådhuset in the south to Uppsala Dragarbrunnsgatan in the north. As is the case for the other species, the northern half of the country is completely unrepresented.

The yearly averages of PM$_{2.5}$ are presented in Figure 15. Generally, we see a very good reproduction of the measured concentrations. The largest underestimates can be seen for Burlöv, Göteborg, Norrköping and Uppsala with a difference of 1-1.5 µg/m^3 and there are no stations with significant overestimates. Appendix 7E also shows the percentile values. These all show relatively small differences between observations and model.

Figure 16 shows the Target plot for all urban background stations with a data availability over 75%. These stations all pass the MQO by a wide margin and very low errors. The Modelling Quality Objective is thus met.

The indicator RDE is calculated for the PM$_{2.5}$ annual mean and is shown in Appendix E. All urban background stations show RDE well below 0.5 (50 %) with the highest being 0.06, and the model quality objective is thus passed.

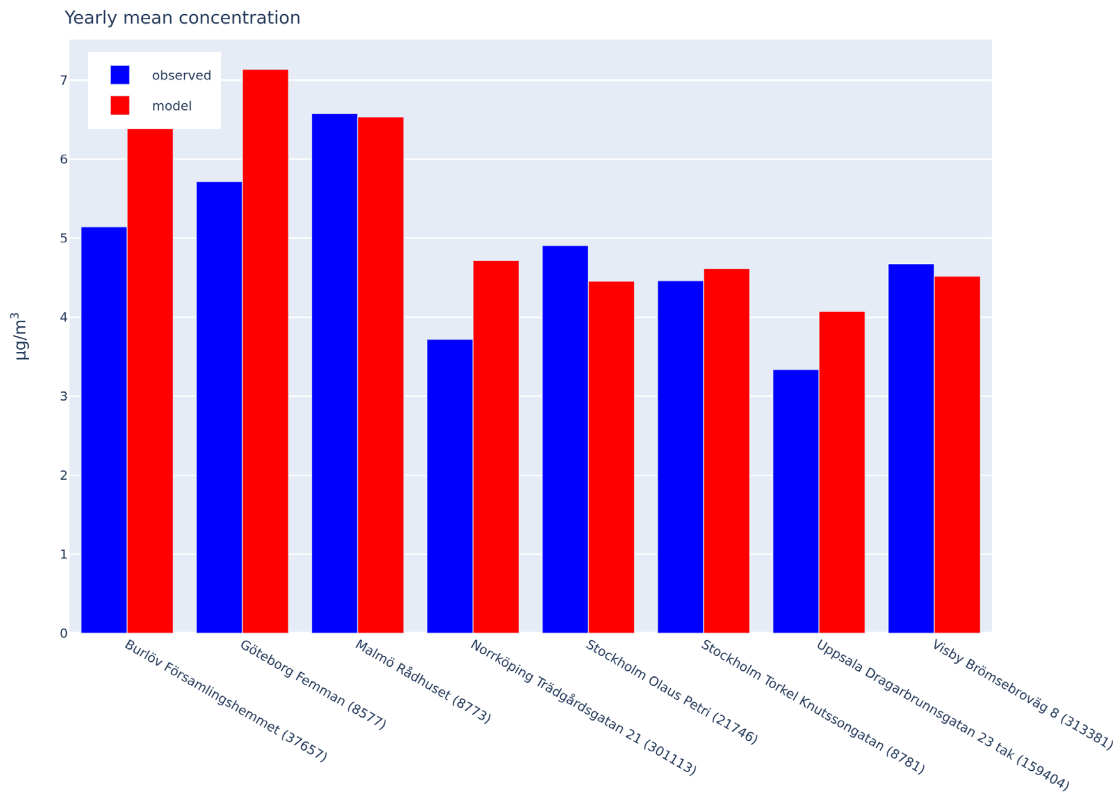

Figure 15. Observed and uncorrected modelled annual means of PM$_{2.5}$ at urban background sites with daily and hourly time resolution data. Model results include a regional and an urban contribution. Measurement stations with lower data coverage than 75% have been excluded.

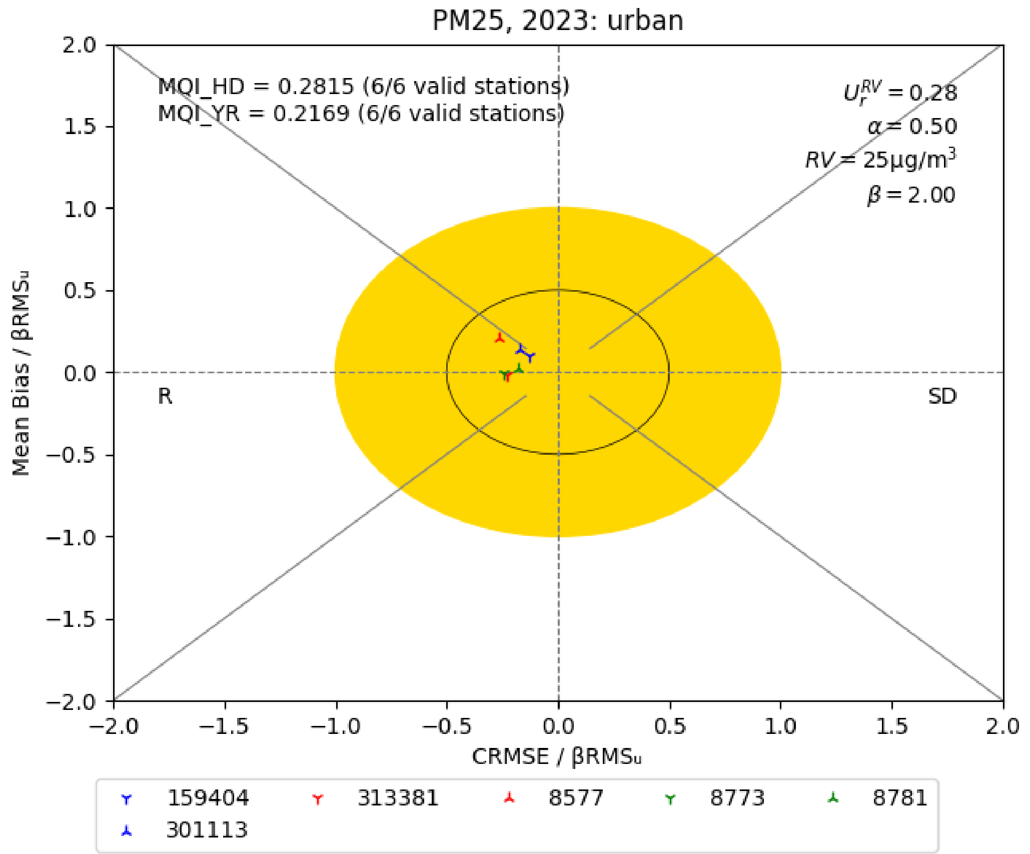

Figure 16. Target plot for $PM_{2.5}$ at urban background sites with hourly time resolution data without urban correction.

3.4.2 Validation at local traffic sites

The validation of $PM_{2.5}$ is made against the 22 stations with hourly measurement data, after having excluded a few stations due to poor placement for modelling purposes or poor data coverage.

The yearly averages for all stations are shown in Figure 17. The model produces good results for the majority of stations. At a couple of stations (Botkyrka Kumla gårdsväg and Västerås Stora Gatan), the modelled concentrations are underestimated by about 2 µg/m^3. At Umeå Västra Esplanaden, the modelled concentrations are instead significantly overestimated by about 2 µg/m^3. In Appendix 7F, we also show the results for the percentiles. We generally see small differences here, with the exception of Botkyrka, Umeå and Östersund for some percentiles.

Appendix 7F includes time series data of daily $PM_{2.5}$ concentrations for six selected stations. In the southern half of the country, the regional contribution dominates while in the northern half the peaks are driven primarily by local traffic and street canyon effects. Overall, there is a less clear seasonal pattern observed for total concentrations of $PM_{2.5}$ than for PM_{10}. Concentrations vary throughout the year and peaks are observed during all seasons. The seasonality that is apparent relates to local traffic contributions during spring months and late autumn/early winter, especially in the northern cities (e.g. Sundsvall and Östersund). At Umeå Västra Esplanaden, the peaks are driven by local effects and in a similar way to PM_{10} show significant overestimations when compared to measurements.

Figure 18 shows the Target diagram for the local traffic stations. The high quality of the results are shown also here and the Model Quality Objective is fulfilled for all stations. The largest error is seen from Umeå Västra Esplanaden, but this one is still within target (T<1).

The indicator RDE for the annual mean is shown in Appendix F. Good results are shown here as well, with the largest deviation again coming from Umeå Västra Esplanaden at 0.11, well below the requirement of 0.5 (50 %).

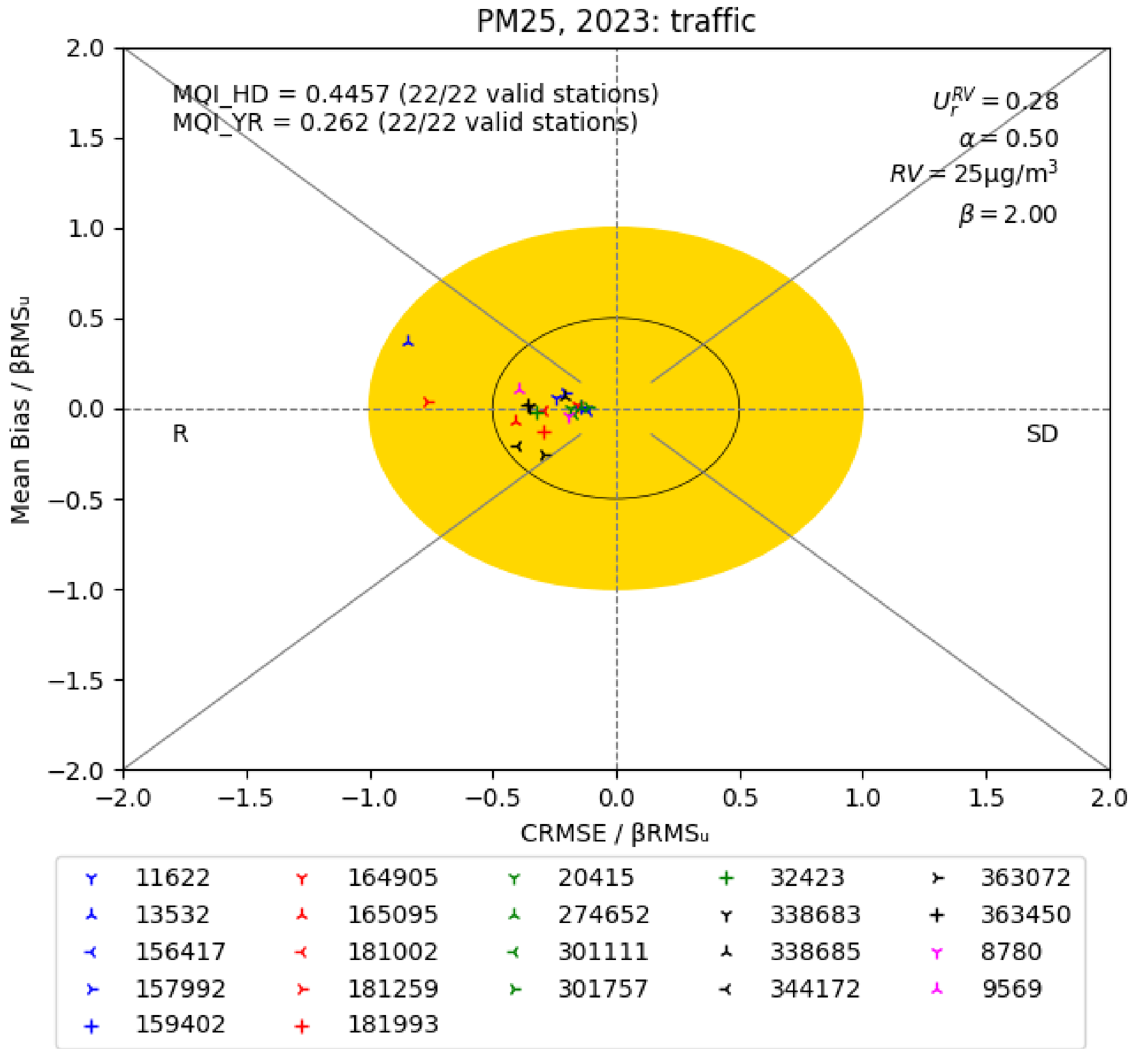

Figure 17. Target plot for $PM_{2.5}$ at local traffic sites with hourly time resolution data.

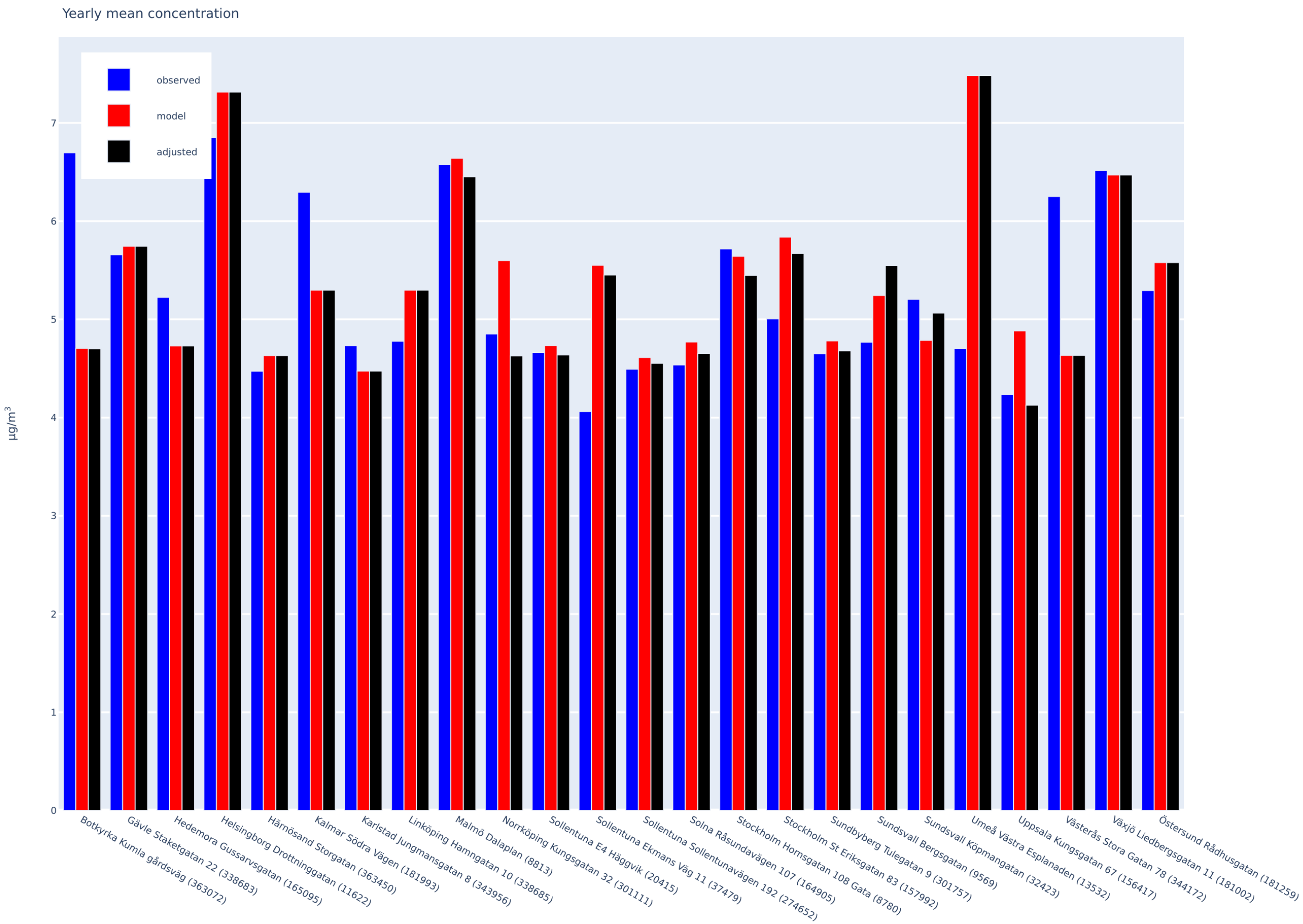

Figure 18. Yearly mean concentrations of $PM_{2.5}$ at traffic sites with hourly measurements. Red bars signify modelled values without urban correction. Black bars signify modelled values including urban correction. Total model concentrations in street canyons include regional, urban and street canyon contributions. A majority of the stations are located within street canyons surrounded by buildings. Measurement stations with lower data coverage than 75% have been excluded.

4 Results

This section gives a brief overview of the national results produced for year 2023. The results include yearly averages and percentiles for NO_2, PM_{10} and $PM_{2.5}$ over all of Sweden. The source contributions are included from regional, urban and street canyon contributions, with the urban contribution further divided into traffic exhaust and non-exhaust, small-scale residential heating, shipping and other sources.

These results are all presented and available for anyone to view on the website for "Nationell modellering av luftkvalitet"[19]. In the following sections, we therefore only give a brief overview of the results along with comparisons to the air quality standards for the yearly averages. We present the results for NO_2 in section 4.1, the results for PM_{10} in section 4.2 and the results for $PM_{2.5}$ in section 4.3.

4.1 NO_2

Figure 19 shows how the annual mean concentration of NO_2 varies throughout the country for regional and urban contributions. We also include the street canyon contribution as filled circles for receptor points above 16 µg/m^3, slightly below the annual mean air quality standard at 20 µg/m^3 defined in the updated EU Ambient Air Quality Directive. This is to take account of uncertainties of the modelled concentrations, which show a slight degree of underestimation. Outside of cities, the regional contribution goes from 4 µg/m^3 in the south to around 1 µg/m^3 in the very north. In urban areas and around major roads, the urban and street canyon contributions dominate with significantly higher concentrations than the regional background.

We see no exceedances of the current annual air quality standard of 40 µg/m3, with the highest concentrations of around 30 µg/m^3 reached at the E6 highway in Gothenburg and at Skeppsbron in Gamla Stan, Stockholm. These cities are also shown in Figure 20 and Figure 21.

Compared to the 20 µg/m^3 limit value, we also predict exceedances at Gruvgatan and Engelbrektsgatan in Falun and at or near major highways in Göteborg and Stockholm. Malmö, Helsingborg, Norrköping, Uppsala, Umeå and Luleå all have concentrations above 16 µg/m^3 and would also risk exceedances.

When comparing to the WHO guideline of 10 µg/m^3, there are exceedances in roughly 30 more cities and towns such as Landskrona, Karlskrona, Alingsås, Jönköping, Linköping, Örebro, Uppsala, Borlänge, Falun, Östersund, Örnsköldsvik, Umeå and Luleå.

[19] https://natmodluft.smhi.se/

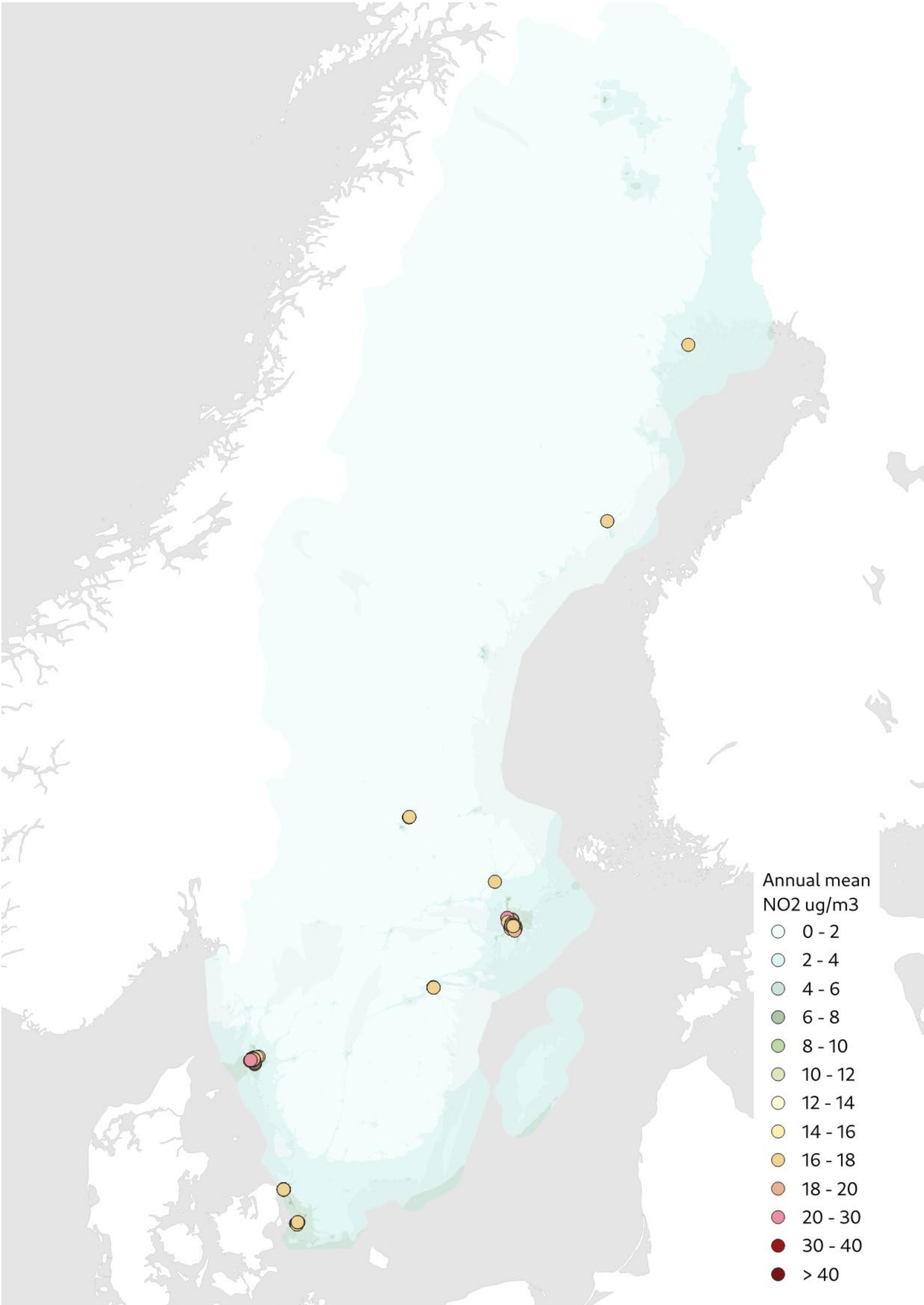

Figure 19. Annual mean concentrations of NO_2 across Sweden 2023.

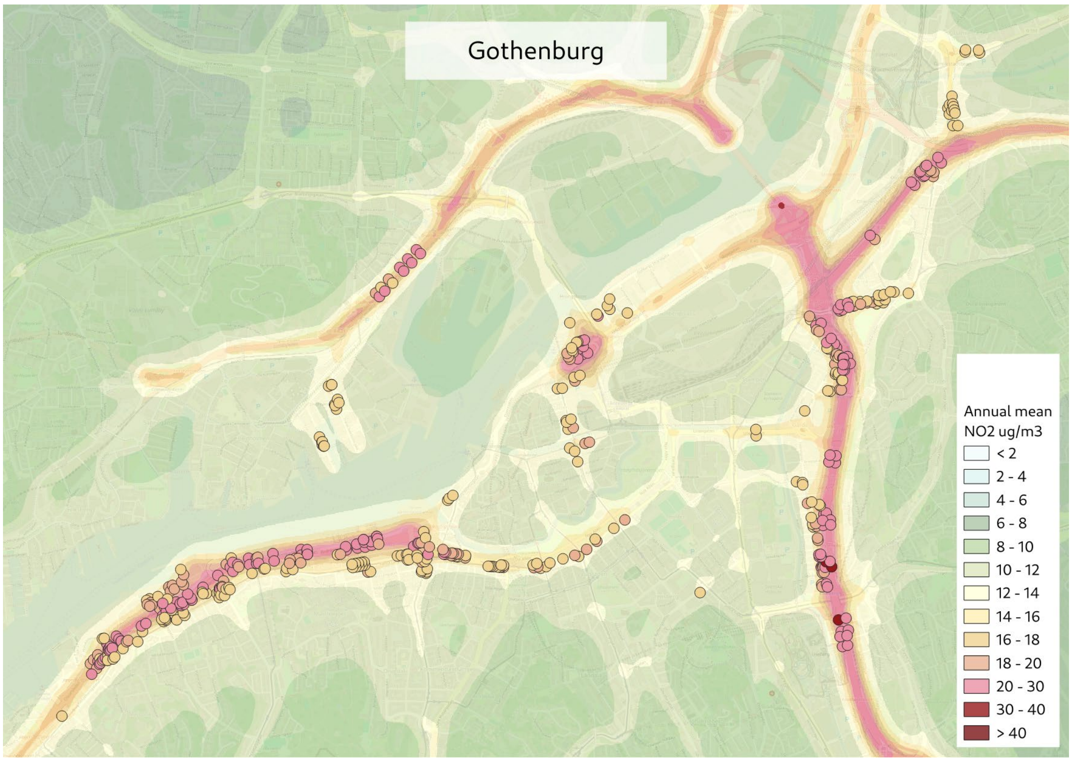

Figure 20. Annual NO_2 concentrations over Gothenburg 2023. Circles represent the total concentration from regional, urban and street canyon contributions. Fields represent background concentrations from regional and urban contributions. Background map: OpenStreetMap.

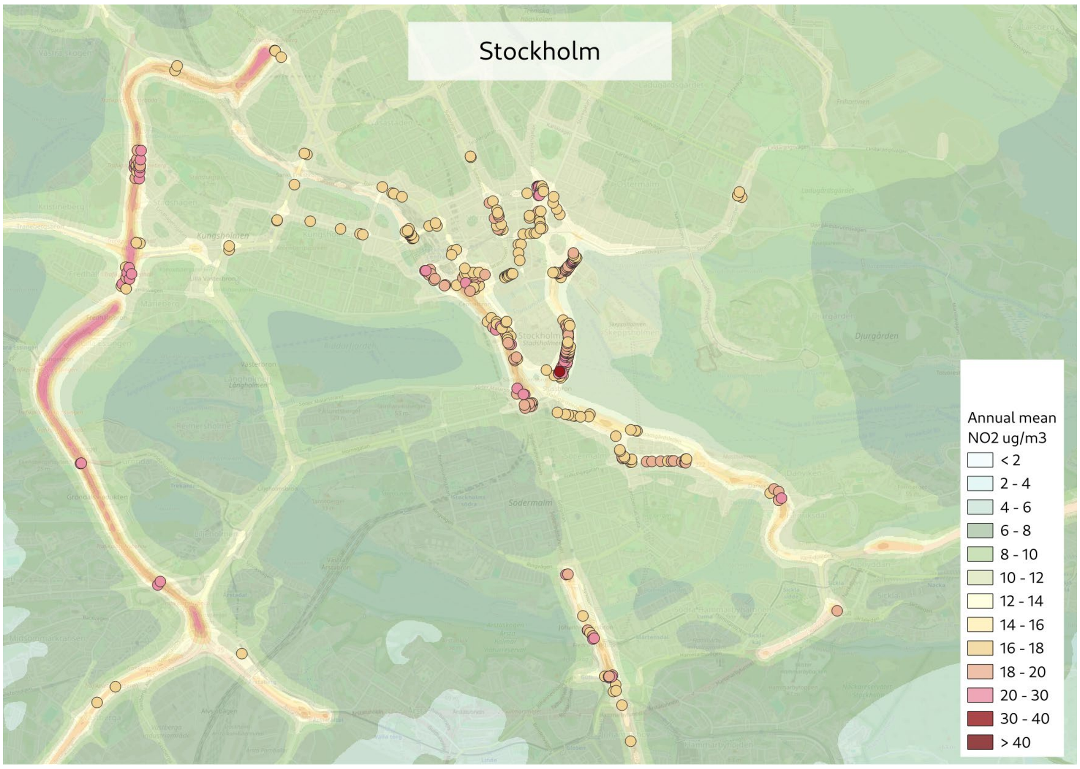

Figure 21. Annual NO_2 concentrations over Stockholm 2023. Circles represent the total concentration from regional, urban and street canyon contributions. Fields represent background concentrations from regional and urban contributions. Background map: OpenStreetMap.

4.2 PM_{10}

Figure 22 shows the annual mean concentration of PM_{10} across all of Sweden. We also include the street canyon contribution as filled circles for receptor points above 16 µg/m^3, slightly below the annual mean air quality standard at 20 µg/m^3 air quality standard defined in the updated EU Ambient Air Quality Directive to take account of uncertainties in the modelling. Annual PM10 concentrations are generally highest in southwestern Sweden and decrease northwards as the regional contribution decreases. In urban areas, PM_{10} levels increase near roads mainly due to non-exhaust traffic-related emissions such as road wear.

No exceedances are seen for the current air quality standard of 40 µg/m^3, but the highest concentrations are reached at Essingeleden south of Gröndalsbron with a concentration of 39 µg/m^3. A couple of other locations in Stockholm and Gothenburg also see concentrations exceeding 30 µg/m^3. Stockholm is shown in Figure 23.

Compared to the 20 µg/m^3 limit, we predict exceedances in twelve different cities in Sweden; Gothenburg, Borås, Jönköping, Stockholm, Västerås, Ludvika, Falun, Sundsvall, Östersund, Skellefteå, Umeå and Luleå. For concentrations above the 16 µg/m^3 limit, the total number of exceedances is 31 cities. In Figure 24, we show Falun as an example where these results predict possible need for further monitoring to fulfil the requirements under the new AAQD.

When comparing to the WHO guideline of 15 µg/m^3, there are exceedances in 40-50 cities or towns.

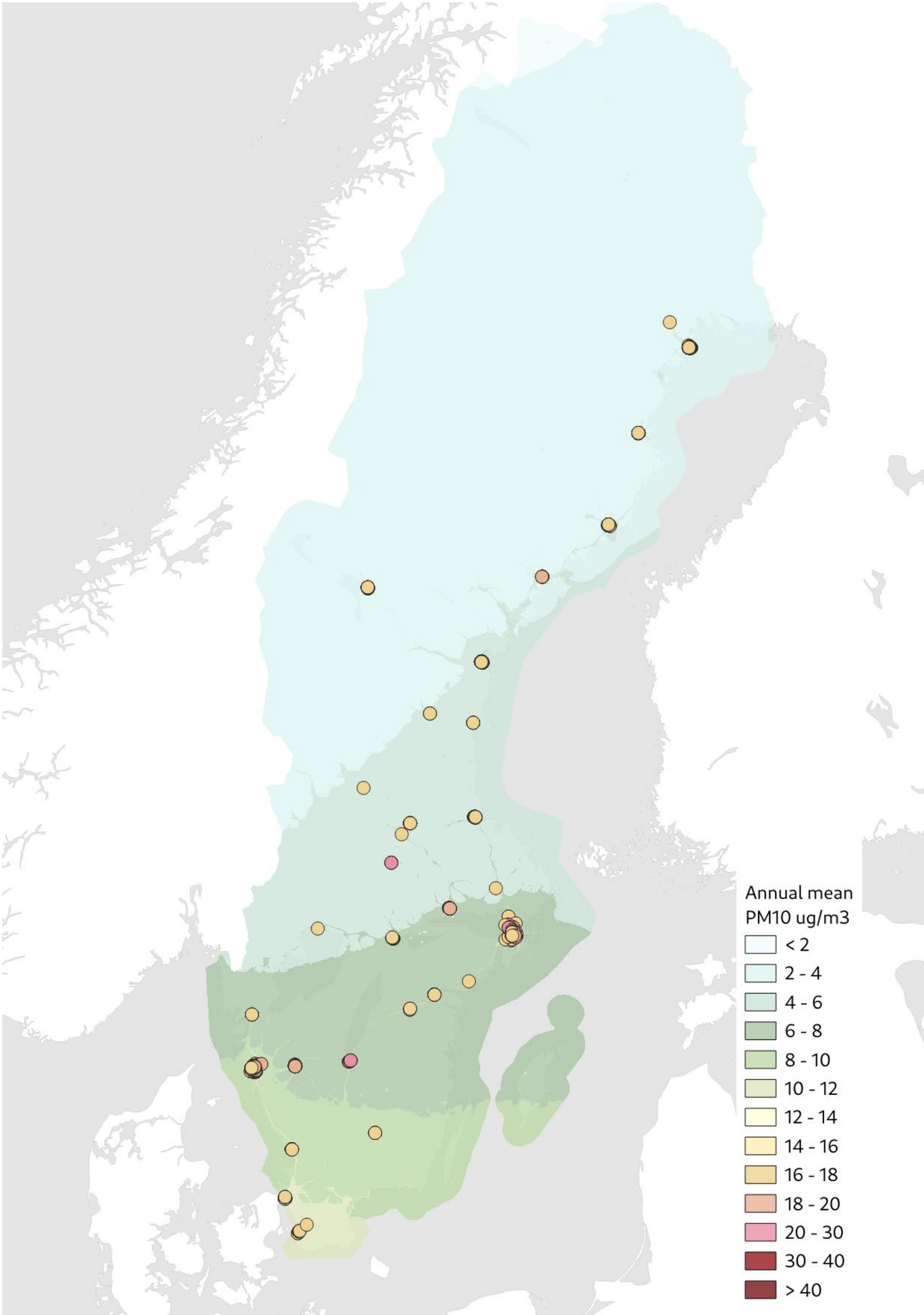

Figure 22. Annual mean concentrations of PM_{10} across Sweden 2023.

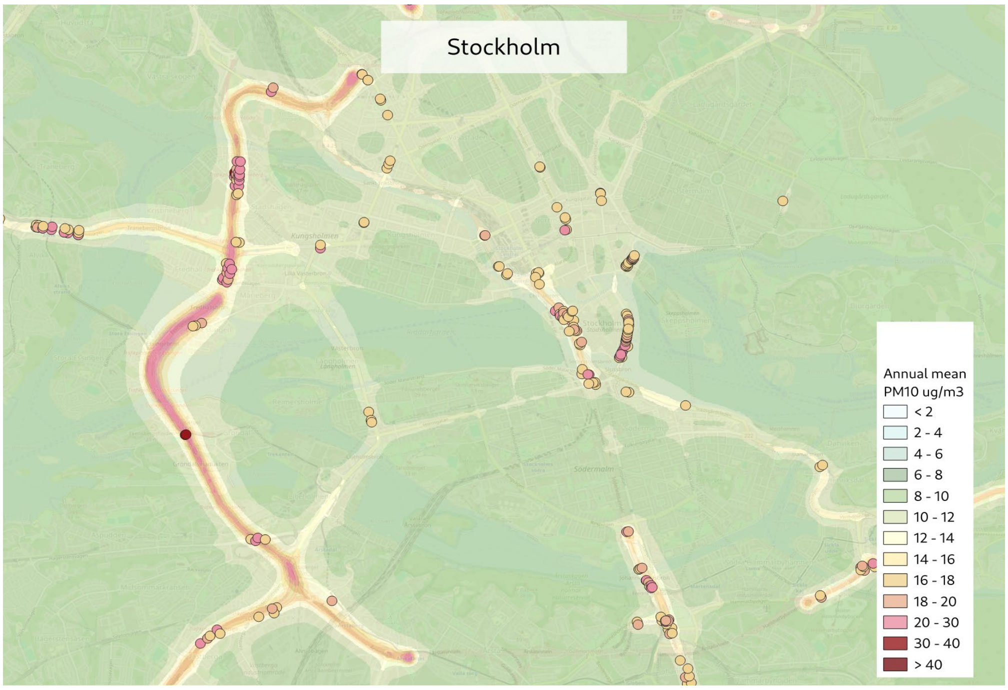

Figure 23. Annual PM_{10} concentrations over Stockholm 2023. Circles represent the total concentration from regional, urban and street canyon contributions. Fields represent background concentrations from regional and urban contributions. Background map: OpenStreetMap.

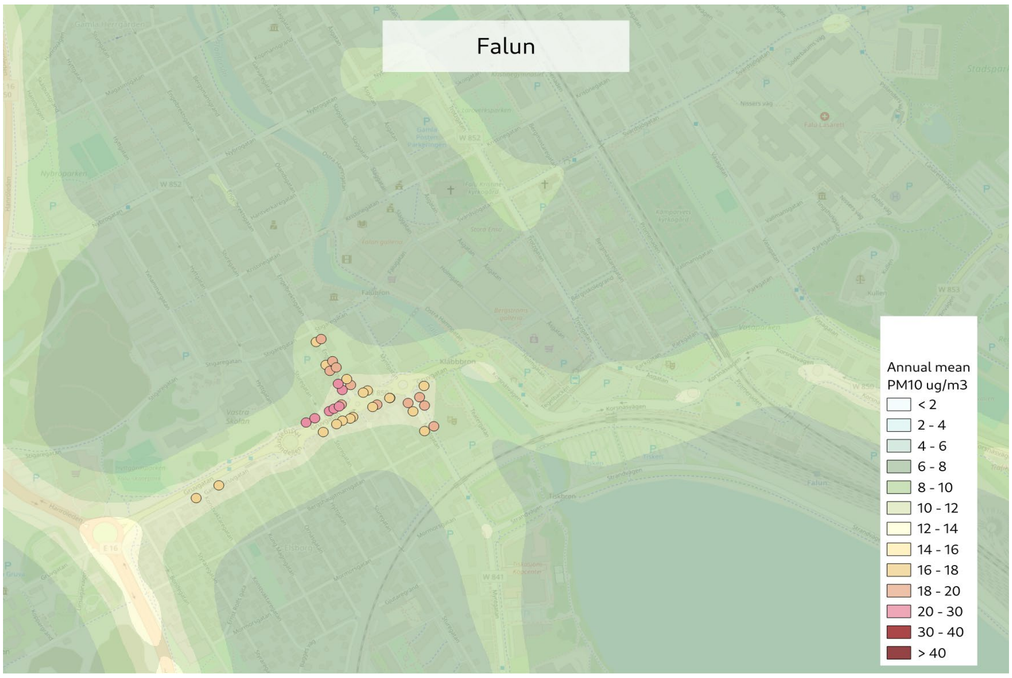

Figure 24. Annual PM_{10} concentrations over Falun 2023. Circles represent the total concentration from regional, urban and street canyon contributions. Fields represent background concentrations from regional and urban contributions. Background map: OpenStreetMap.

4.3 $PM_{2.5}$

Figure 25 shows the annual mean concentration of $PM_{2.5}$ over the country. We also include the street canyon as filled circles for receptor points above 7 µg/m^3. Concentrations are generally very low and are mainly dominated by international regional contributions. Because of this, they are the highest in the south of Sweden with regional contributions up to 6 µg/m^3 decreasing to about 1.5 µg/m^3 in the very north.

The highest yearly averages are therefore found in the southern parts of the country, with concentrations above 7 µg/m^3 in Malmö and Helsingborg. There is also a point source outside of Bengtsfors in Dalsland that contributes enough to exceed 7 µg/m^3, but this would need to be verified in further studies. Outside of the cities there are also stretches of highway, between for example Malmö and Gothenburg and within Stockholm, with concentrations between 6 and 7 µg/m^3, but these concentrations are very local and likely don't lead to significant population exposure.

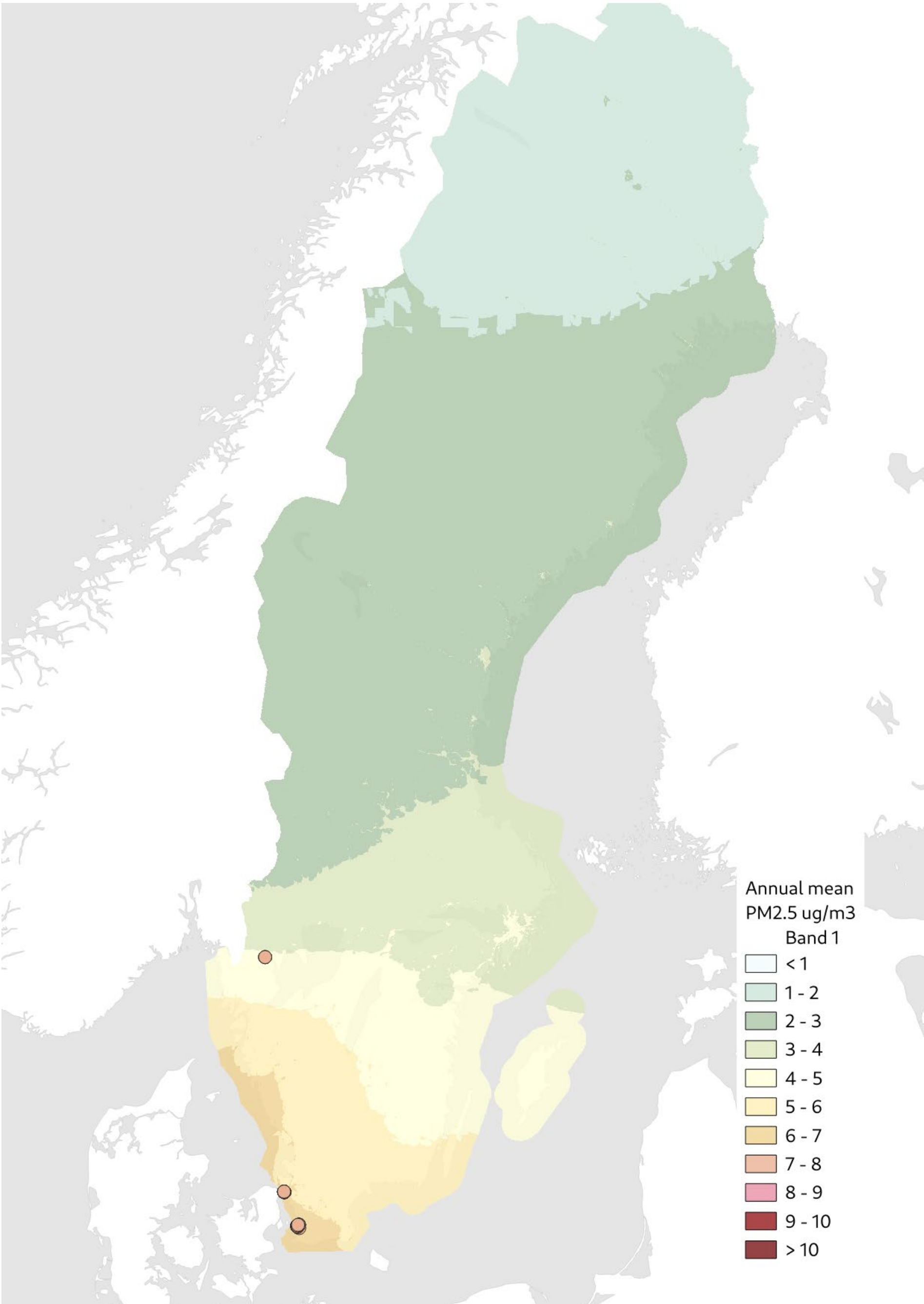

Figure 25. Annual mean concentrations of $PM_{2.5}$ across Sweden 2023.

5 Conclusions

This is the second project for modelling of national high-resolution concentrations over Sweden. It is meant to provide a high quality overview of the air quality over the whole country. It will also continue to serve as a national base dataset for evaluating air quality in Sweden and as preparation ahead of the updated AAQD, that is to be legally binding by 2030.

The data set can be used to detect hot spot areas anywhere in the country and identify places where the current or future air quality standards risk being exceeded. It can also serve as a guide for the future placement of measurement stations by helping municipalities to identify where the highest concentrations can be found as well as in the development of action plans for air quality mitigation. The new urban source apportionment data that has been made available through this project is a powerful tool that can give additional information on the main emission sources at any location.

This project has focused on improving the models and emission data, but more work will be needed to improve the model quality for it to pass all the data quality objectives for the whole country. As it is, it should be stressed that a more detailed local study might be needed to fully understand the air quality at given locations.

The model and emission updates have led to a significant quality improvement of the modelled NO_2 concentrations. The MQO is now passed for all urban and traffic stations, and the model results now pass the annual mean quality objective for all stations and the other quality objectives for 80 % of the traffic stations. As a result of the improved model quality, the NO_2 percentiles have now been made available on the website for public viewing.

For PM_{10}, significant work was dedicated to improving the non-exhaust emissions from traffic and also with respect to other emission sources. This however led to mixed results. For the urban stations, the MQO now passed at yet higher quality than the 2019 results. For the traffic stations, we now see better agreement of the annual mean concentrations and the annual mean quality objective, but with fewer stations passing the MQO. It can however be noted that the sample size is larger now, with 32 stations of which 8 are located in Norrland in this project, while in the 2019 project there were 27 stations in total of which only 2 were located in Norrland. A large number of new traffic stations have also been added while some stations from 2019 are no longer active. We also have no information on dust binding and have, in this work, assumed zero usage of dust binding agents. If the use has increased in the later years, this could also explain some differences. These reasons might all contribute to the overall poorer result for the MQO in this project.

For $PM_{2.5}$, the quality has been consistently high with some smaller quality improvements since the last project. All stations pass the MQO and all stations pass the annual mean quality objective.

It should also be noted that modelling extreme values (percentiles) continues to be difficult. We generally see some improvements with this work, but continued effort is needed to reach better agreement between measurements and models at higher concentrations.

A lot of work has also been done to improve the emissions outside of the range of the measurement stations. This includes improvements to the industrial point sources, shipping emissions and road traffic data. It is recommended that further work be prioritised to continue to improve the traffic data, such as traffic numbers, assumptions on road gritting with sand and assumptions regarding the use of dust binding agents. These activities would likely be among those with the highest impact on the model quality. This also includes further collaboration with Trafikverket as well as more traffic measurements being added to the databases maintained by Trafikverket. Continued work to improve emissions on a broad scale for other emission sectors would also be very important.

Further work would also be needed to continue to improve the model system and model parameterisation. This would include reviewing and improving different dispersal processes, model methodology and computation methodology. The effort carried out in this work to improve the calculation speed allows for more trial runs to be done to test and evaluate different parameter sets.

We also want to point out the importance of carrying out frequent simulation cycles to maintain and transfer knowledge and competence within the modelling team. In practice, the work necessary for improving model quality requires continuous focus.

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7 Appendix

A. Results for NO_2 at urban stations

Urban background site	RDE Annual mean	RDE Hourly 98 perc.	RPE Hourly 98 perc.	RDE Daily 98 perc.	RPE Daily 98 perc.
Falun Östra Falan	0.14	0.66	0.71	0.60	0.71
Uppsala Dragarbrunnsgatan 23 tak	0.01	0.27	0.06	0.05	0.00
Landskrona Storgatan 24	0.06	0.41	0.36	0.24	0.40
Norrköping Trädgårdsgatan 21	0.02	0.00	0.06	0.05	0.13
Göteborg Femman	0.06	0.15	0.22	0.19	0.28
Malmö Rådhuset	0.03	0.28	0.03	0.03	0.20
Stockholm Torkel Knutssongatan	0.01	0.25	0.34	0.05	0.37
Lund Spyken	0.02	0.12	0.16	0.17	0.24
Mölndal Göteborgsvägen Tak	0.13	0.47	0.47	0.56	0.58
Helsingborg Norr	0.08	0.50	0.30	0.26	0.38
Max value	0.14	0.66	0.71	0.60	0.71

Table 5. RPE and RDE values for NO_2 at urban background sites with hourly time-resolution.

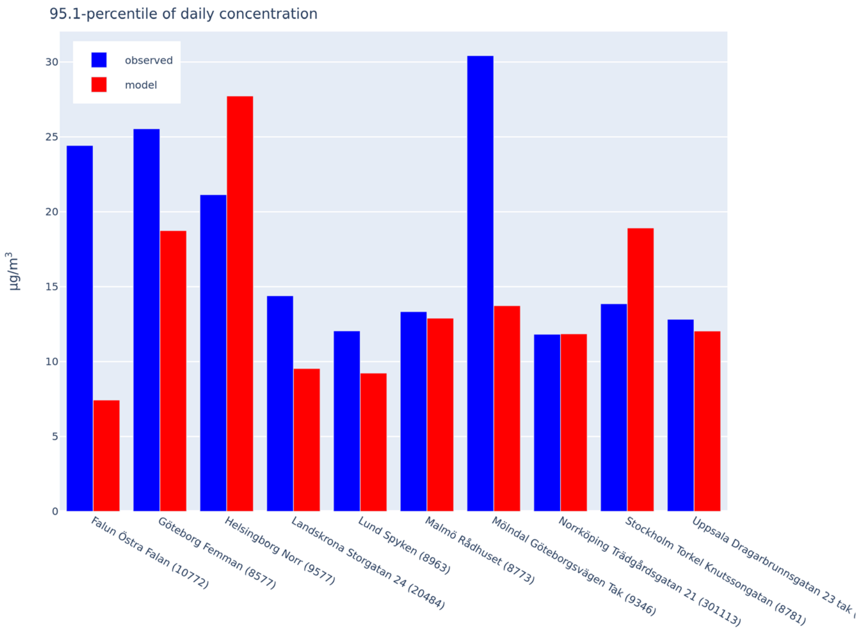


Figure 26. Modelled and observed NO_2 95.1 percentile at urban background sites. This is the new daily limit value at 50 µg/m^3 proposed in the revised EU Ambient Air Quality Directive. Observed (blue bars) and modelled (red bars).

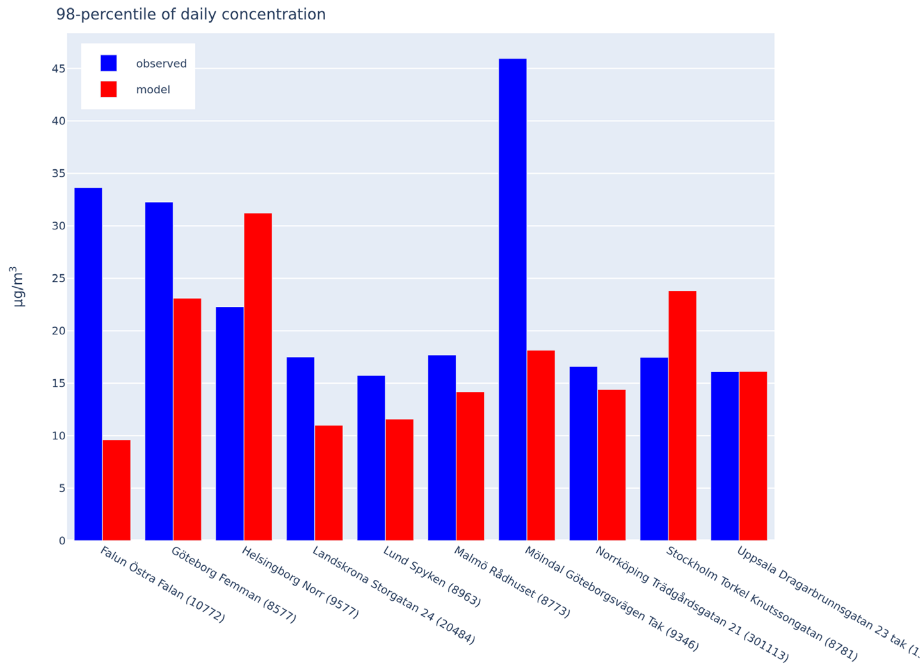


Figure 27. Modelled and observed NO_2 98th percentile at urban background sites. This is the current daily limit value at 60 µg/m^3. Observed (blue bars) and modelled (red bars).

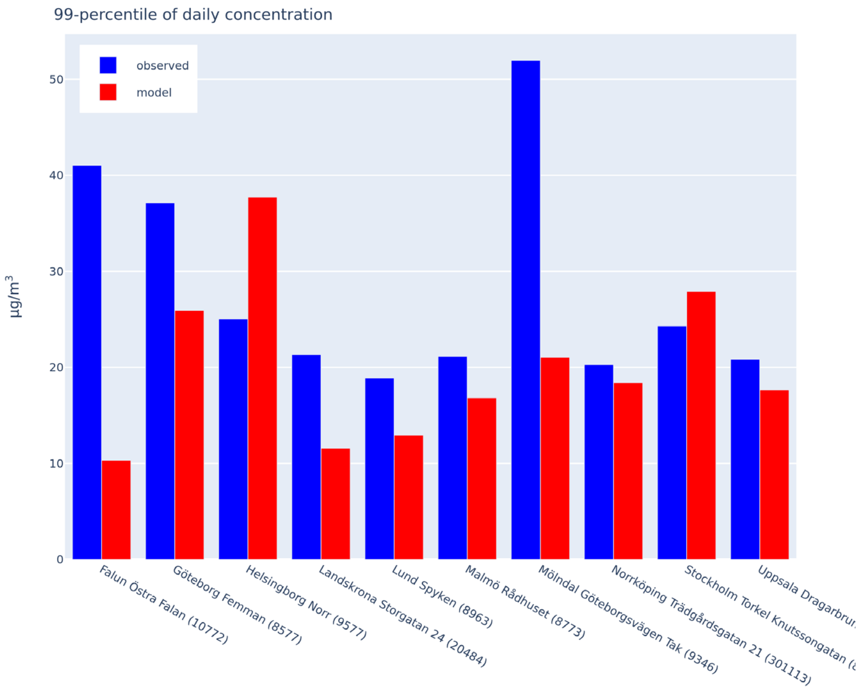


Figure 28. Modelled and observed NO_2 99^{th} percentile at urban background sites. This is the daily limit value at 25 µg/m^3 from the World Health Organisation. Observed (blue bars) and modelled (red bars).

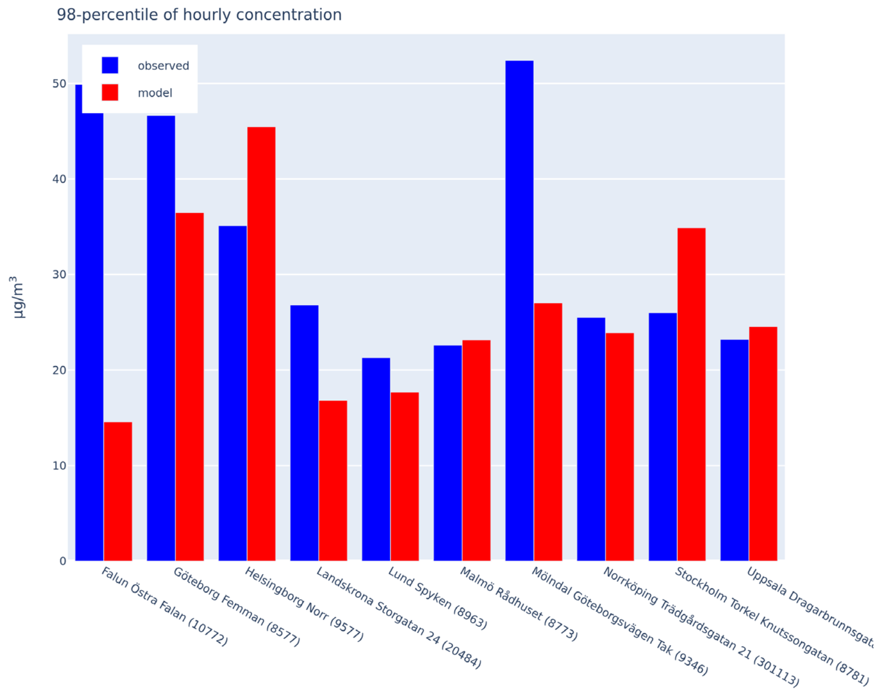


Figure 29. Modelled and observed NO_2 98^{th} percentile at urban background sites. This is the current hourly air quality standard with limit value at 90 µg/m^3 in Sweden. Observed (blue bars) and modelled (red bars).

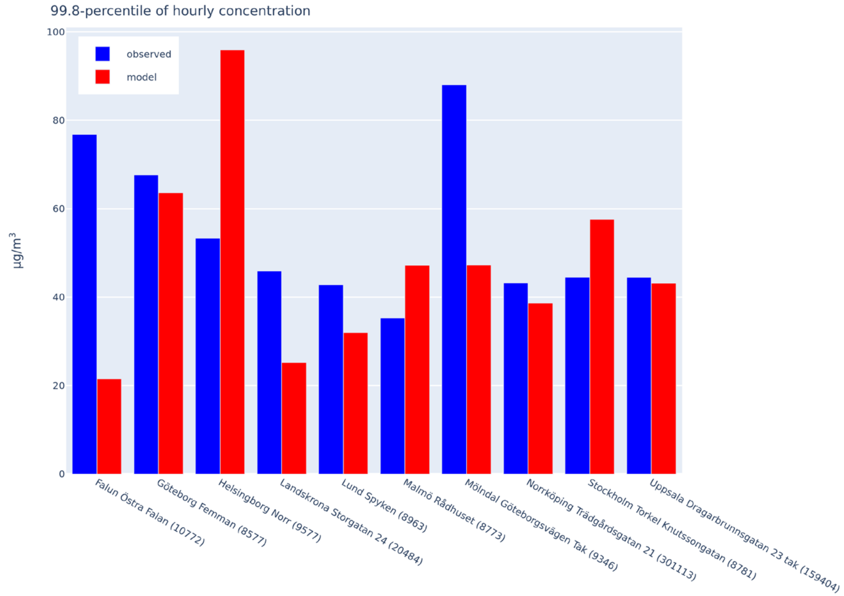


Figure 30. Modelled and observed NO_2 99.8th percentile at urban background sites. This is the current hourly limit value at 200 µg/m^3. Observed (blue bars) and modelled (red bars).

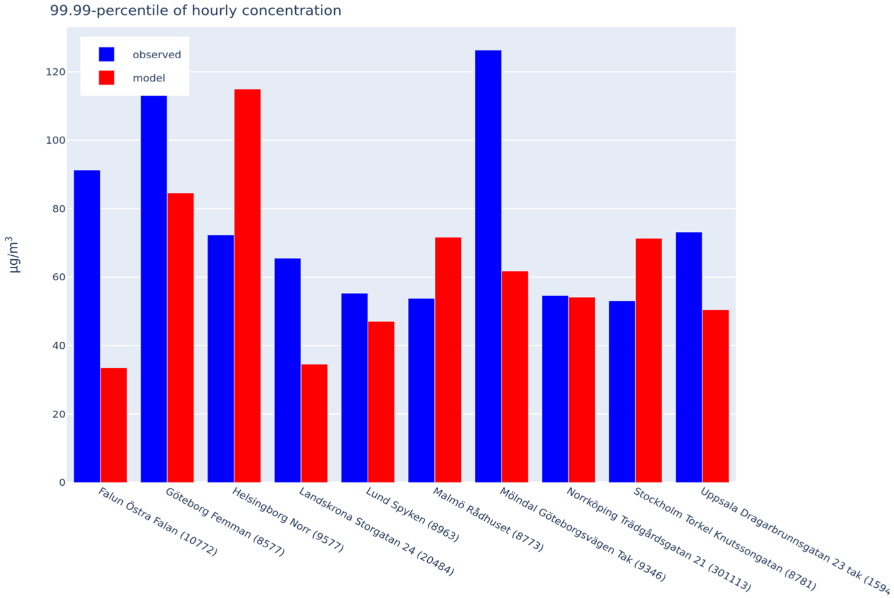


Figure 31. Modelled and observed NO_2 99.99th percentile at urban background sites. This is the new daily limit value at 200 µg/m^3 proposed in the revised EU Ambient Air Quality Directive. Observed (blue bars) and modelled (red bars).

B. Results for NO_2 at local traffic stations

Traffic site	RDE Annual mean	RDE Hourly 98 perc.	RPE Hourly 98 perc.	RDE Daily 98 perc.	RPE Daily 98 perc.
Helsingborg Drottninggatan	0.06	0.42	0.03	0.10	0.14
Umeå Västra Esplanaden	0.20	0.48	0.49	0.54	0.56
Falun Svärdsjögatan 3B gata	0.08	0.25	0.23	0.01	0.11
Trelleborg Hamngatan	0.18	0.42	0.56	0.36	0.50
Uppsala Kungsgatan 67	0.13	0.38	0.20	0.25	0.30
Jönköping Kungsgatan 2A	0.13	0.21	0.27	0.28	0.33
Stockholm St Eriksgatan 83	0.12	0.89	0.37	0.47	0.28
Stockholm E4 Skonertvägen	0.07	0.23	0.05	0.15	0.02
Stockholm Folkungagatan 70	0.04	0.27	0.01	0.05	0.09
Solna Råsundavägen 107	0.09	0.49	0.16	0.25	0.21
Östersund Rådhusgatan	0.23	0.45	0.47	0.53	0.53
Kalmar Södra Vägen	0.12	0.27	0.55	0.20	0.55
Örnsköldsvik Centralesplanaden 15C	0.23	0.45	0.47	0.50	0.50
Sollentuna E4 Häggvik	0.18	0.22	0.20	0.28	0.17
Södertälje Turingegatan 26	0.14	0.34	0.35	0.40	0.41
Halmstad Viktoriagatan	0.11	0.17	0.17	0.19	0.14
Malmö Dalaplan 5B	0.11	0.49	0.03	0.15	0.21
Skellefteå Kv Renen	0.21	0.36	0.37	0.55	0.40
Göteborg Övre Husargatan	0.02	0.56	0.03	0.13	0.06
Stockholm Valhallavägen 14	0.09	0.36	0.21	0.06	0.23
Norrköping Kungsgatan 32	0.01	0.34	0.00	0.14	0.00
Sundbyberg Tulegatan 9	0.07	0.59	0.17	0.30	0.21
Helsingborg M1 Södra Stenbocksgatan	0.05	0.30	0.15	0.05	0.16
Piteå Prästgårdsgatan	0.18	0.69	0.67	0.57	0.66
Borås Kungsgatan	0.12	0.25	0.34	0.55	0.41
Luleå Sandviksgatan	0.01	0.24	0.26	0.58	0.28
Sundsvall Köpmangatan	0.08	0.30	0.08	0.05	0.04
Gävle Staketgatan 22	0.13	0.25	0.26	0.36	0.35
Linköping Hamngatan 10	0.10	0.05	0.34	0.05	0.33
Karlstad Jungmansgatan 8	0.14	0.56	0.55	0.61	0.52
Västerås Stora Gatan 78	0.10	0.16	0.41	0.20	0.37

Botkyrka Kumla gårdsväg	0.27	0.54	0.57	0.44	0.54
Lund Trollebergsvägen	0.07	0.22	0.27	0.25	0.25
Stockholm Sveavägen 59 Gata	0.03	0.87	0.01	0.29	0.04
Stockholm Hornsgatan 108 Gata	0.15	0.08	0.13	0.11	0.12
Malmö Dalaplan	0.04	0.50	0.10	0.21	0.11
Max value	0.27	0.89	0.67	0.61	0.66

Table 6. RPE and RDE for NO_2 annual means and percentiles at traffic stations with hourly time-resolution.

Figure 32. Modelled and observed (black line) daily time-series concentrations of NO_2 at traffic sites in Norrköping (a), Göteborg (b) and Malmö (c). Modelled concentrations show the contributions from regional (blue area), urban (grey area) and street canyons (pink). Concentration unit on y-axis is µg/m^3.

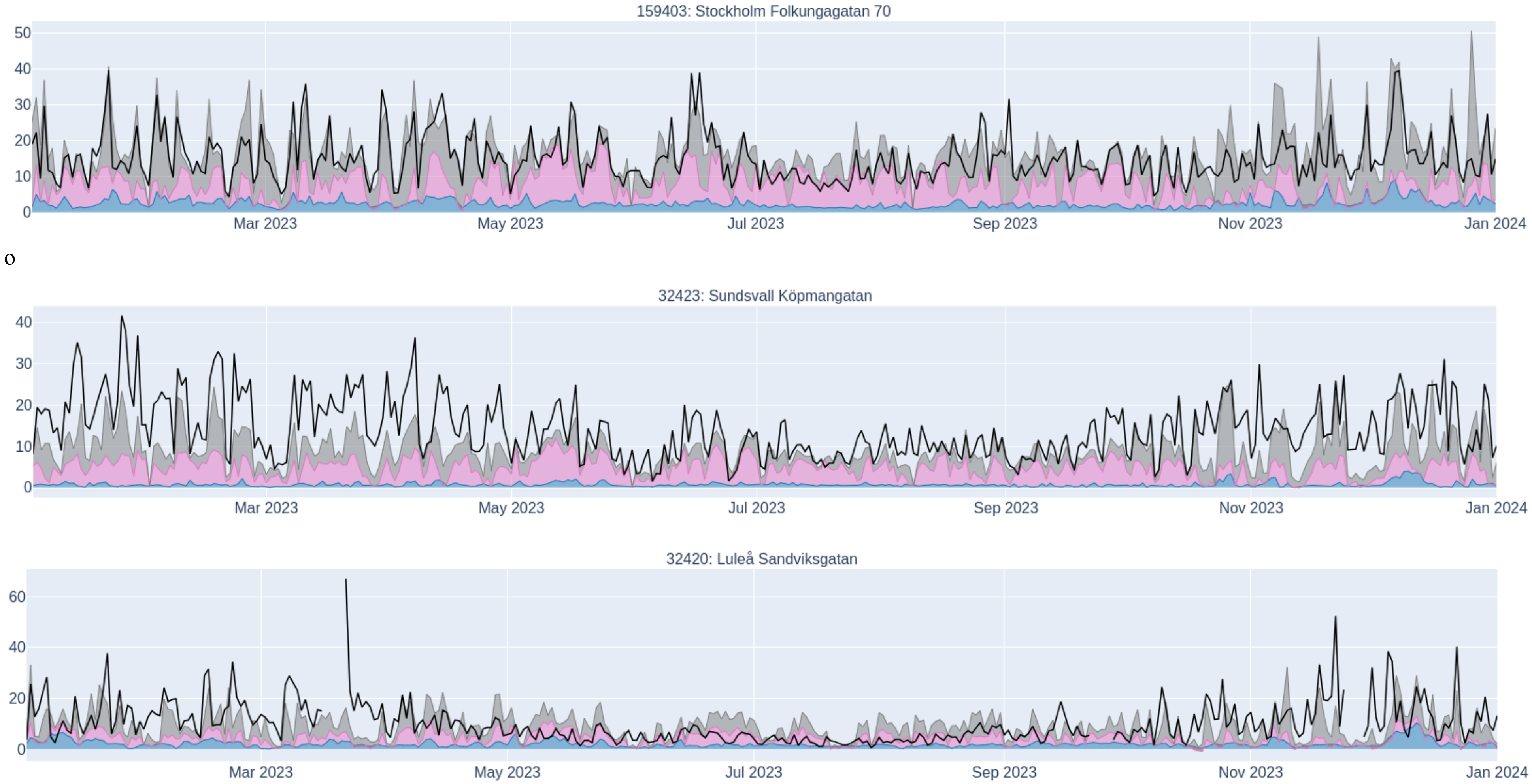


Figure 33. Modelled and observed (black line) daily time-series concentrations of NO_2 at traffic sites in Stockholm (a), Sundsvall (b) and Luleå (c). Modelled concentrations show the contributions from regional (blue area), urban (grey area) and street canyons (pink). Concentration unit on y-axis is µg/m^3.

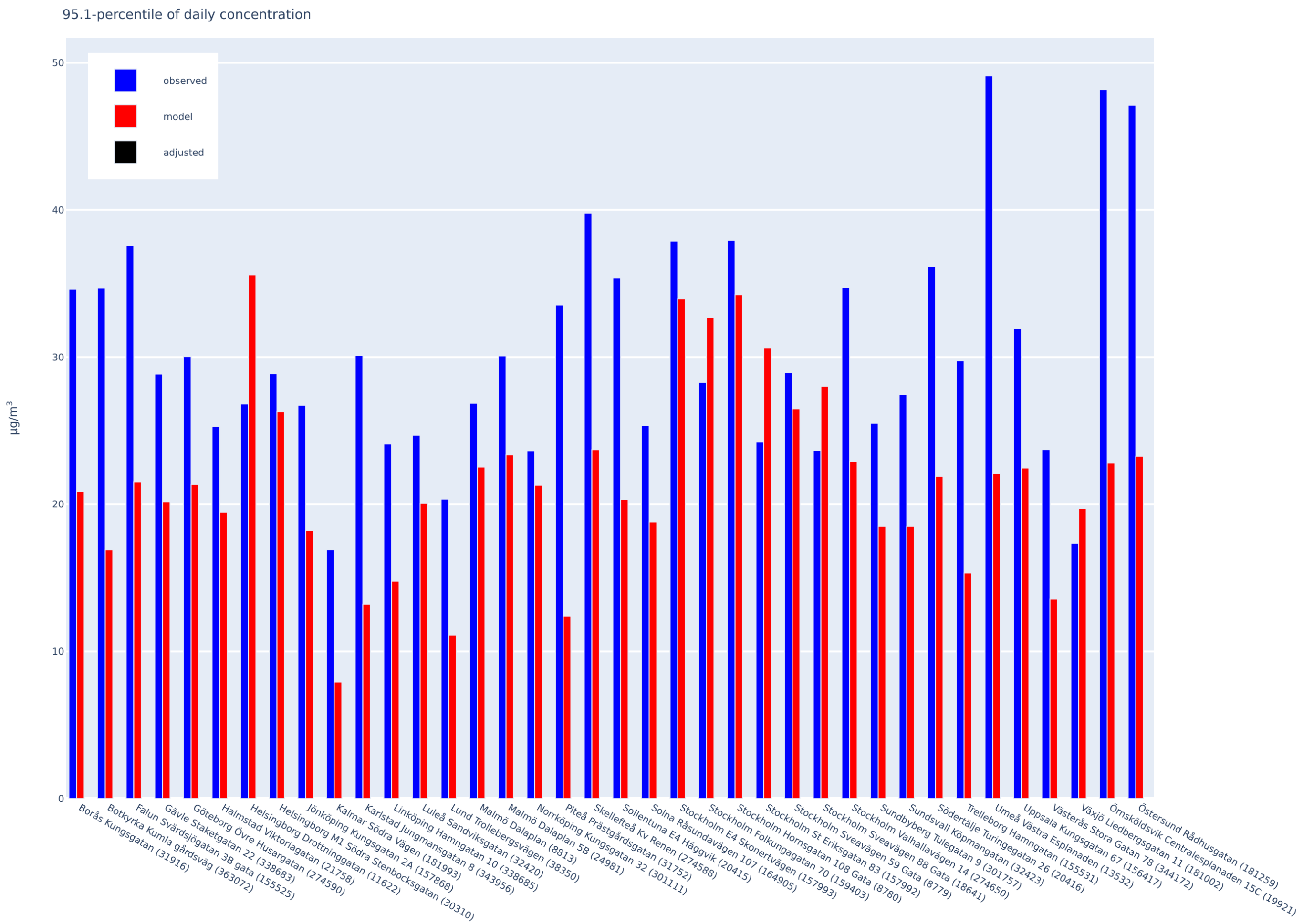


Figure 34. Modelled and observed NO_2 95.1th percentile at local traffic sites. This is the new daily limit value at 50 µg/m^3 proposed in the revised EU Ambient Air Quality Directive. Observed (blue bars) and modelled (red bars) and modelled values adjusted against urban background measurements (black bars).

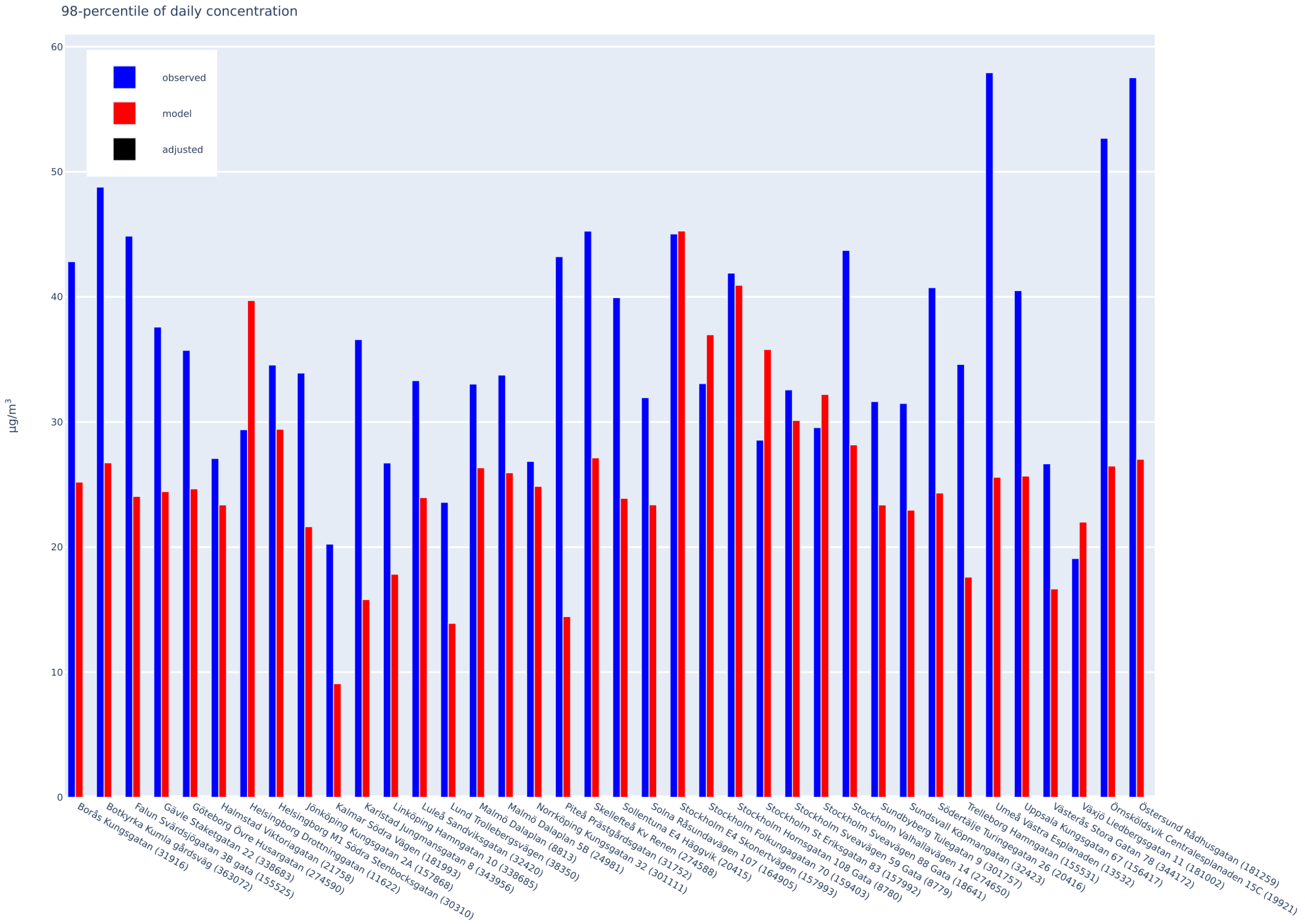


Figure 35. Modelled and observed NO_2 98th percentile at local traffic sites. This is the current daily limit value at 60 µg/m3 in Sweden. Observed (blue bars), modelled (red bars) and modelled values adjusted against urban background measurements (black bars).

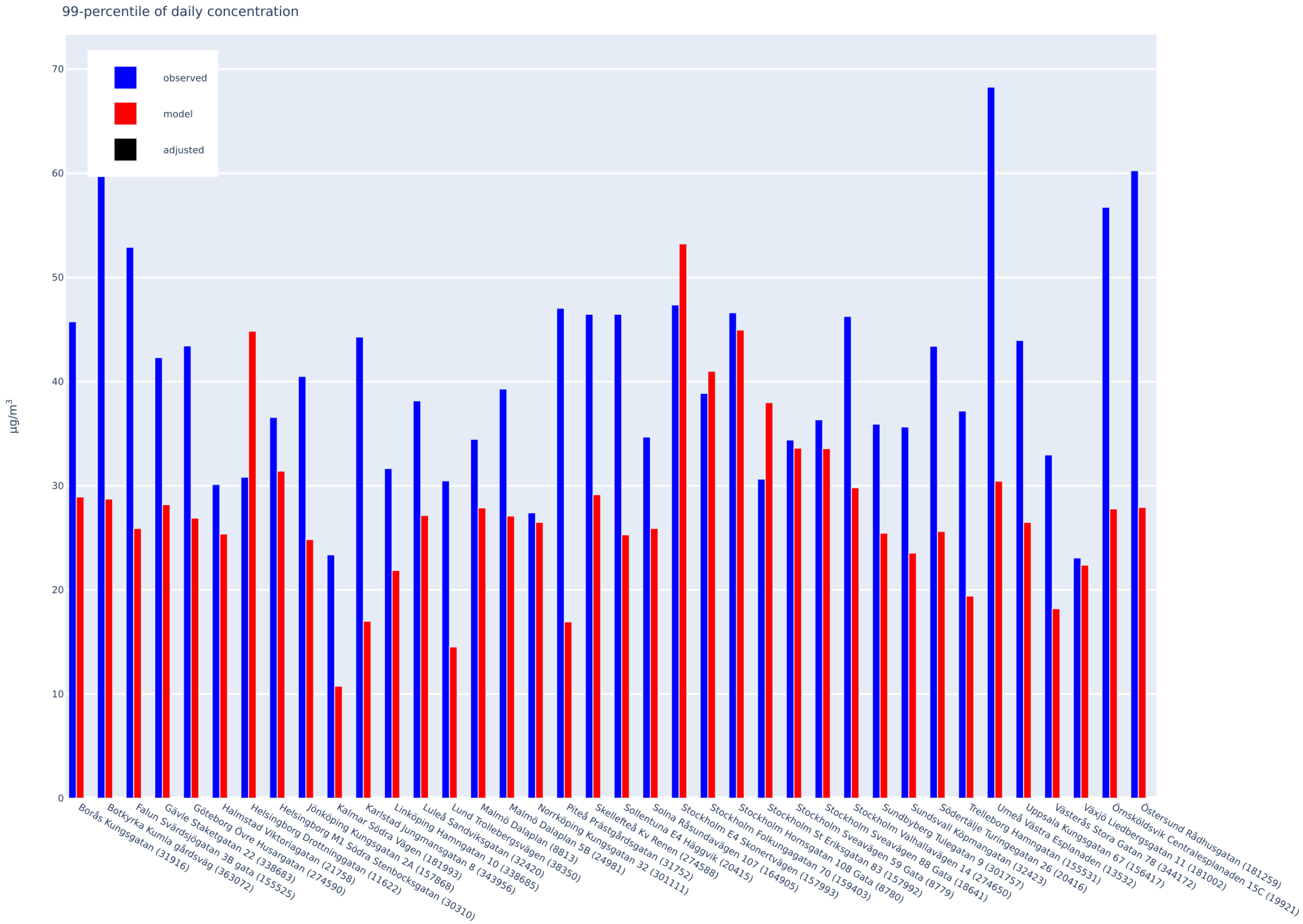


Figure 36. Modelled and observed NO_2 99th percentile at local traffic sites. This is the daily limit value at 25 µg/m3 from the World Health Organisation. Observed (blue bars), modelled (red bars) and modelled values adjusted against urban background measurements (black bars).

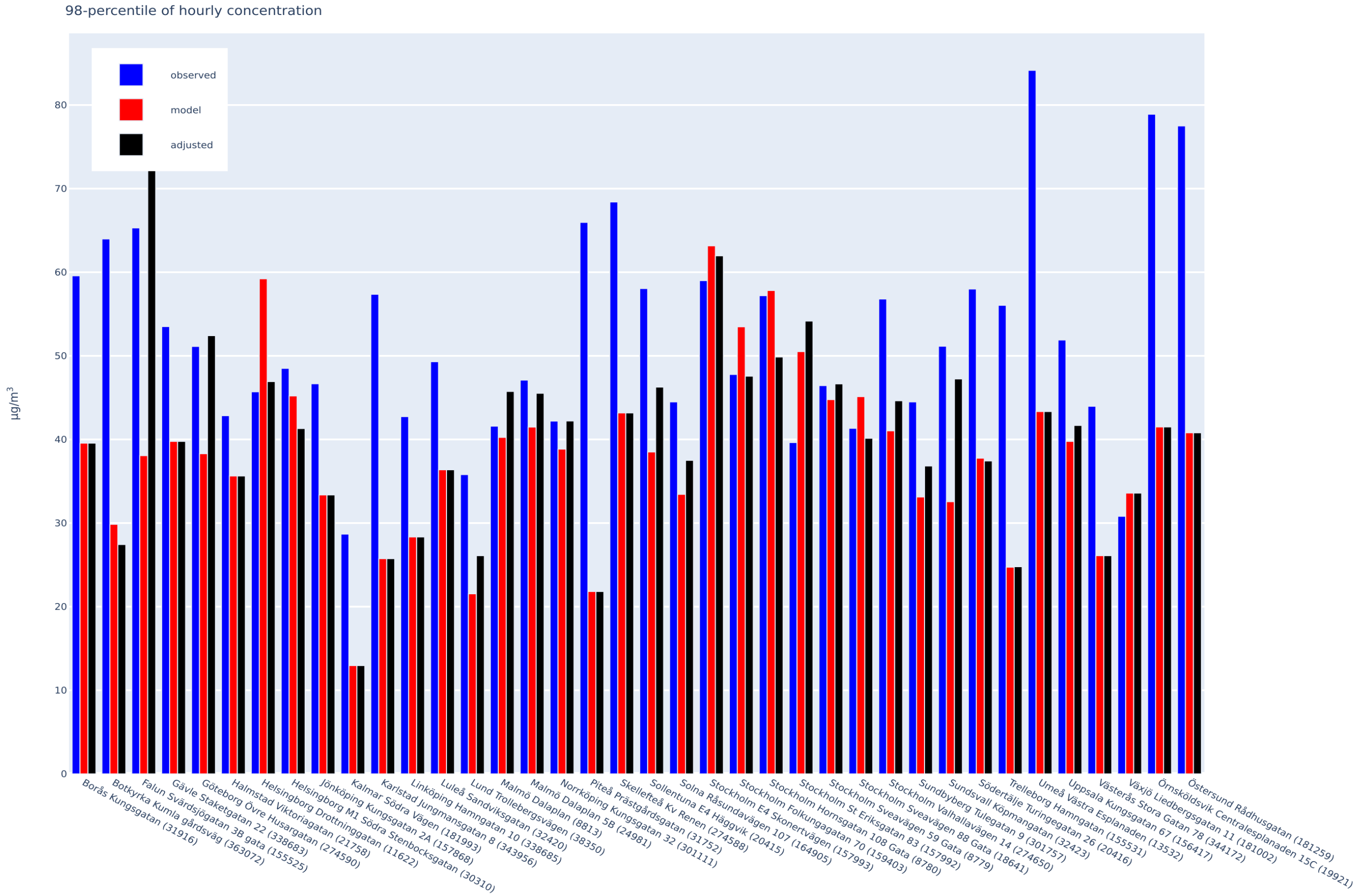


Figure 37. Modelled and observed NO_2 98th percentile at local traffic sites. This is the current hourly limit value at 90 µg/m3 in Sweden. Observed (blue bars), modelled (red bars) and modelled values adjusted against urban background measurements (black bars).

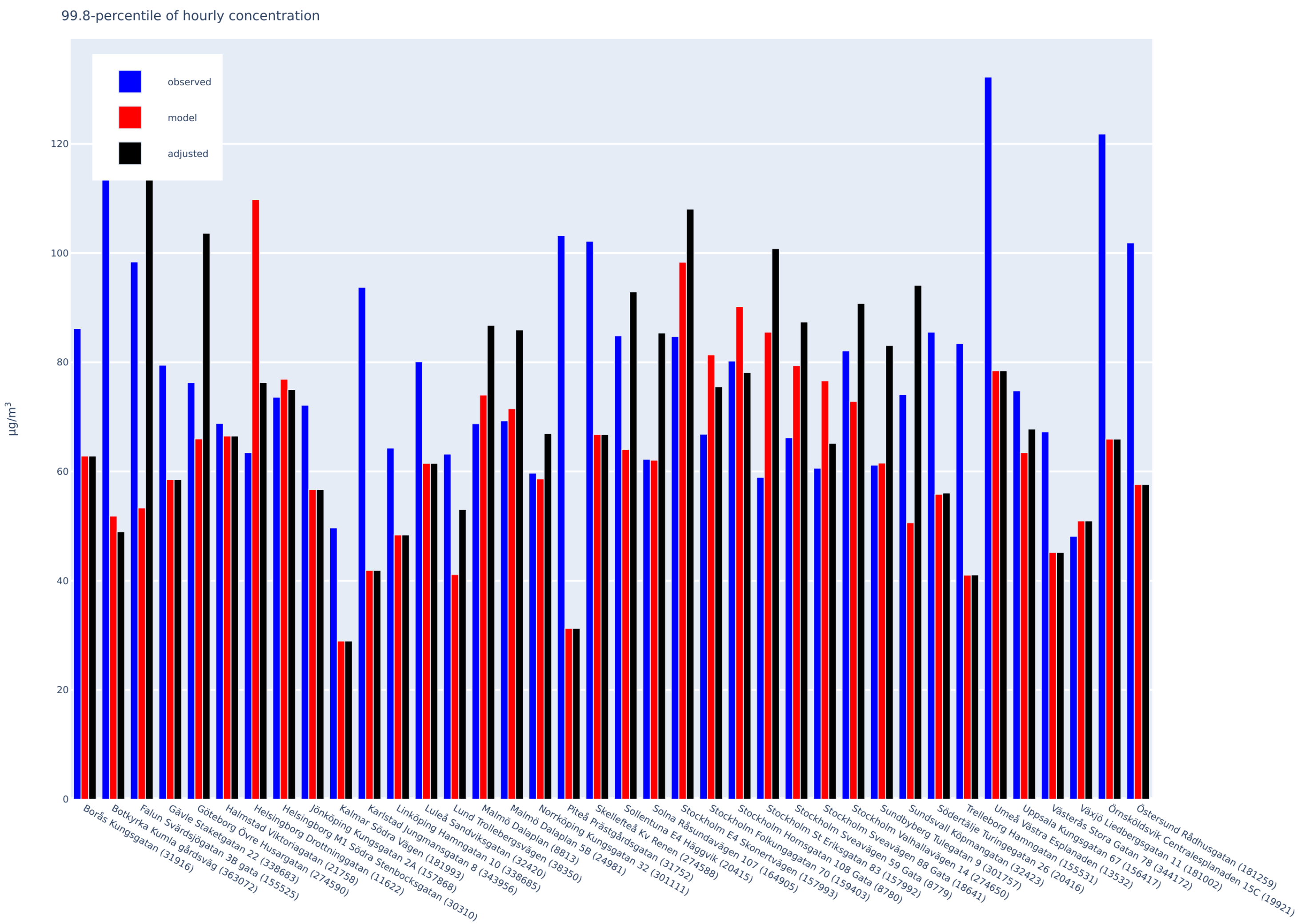


Figure 38. Modelled and observed NO_2 99.8th percentile at local traffic sites. This is the current hourly limit value at 200 µg/m3 in Sweden. Observed (blue bars), modelled (red bars) and modelled values adjusted against urban background measurements (black bars).

C. Results for PM_{10} at urban stations

Urban background sites	RDE Annual mean	RDE Daily 90 perc.	RPE Daily 90 perc.
Uppsala Dragarbrunnsgatan 23 tak	0.03	0.01	0.14
Norrköping Trädgårdsgatan 21	0.03	0.03	0.02
Visby Brömsebroväg 8	0.02	0.59	0.14
Göteborg Femman	0.04	0.0	0.17
Malmö Rådhuset	0.01	0.17	0.04
Stockholm Torkel Knutssongatan	0.01	0.0	0.04
Max value	0.04	0.59	0.17

Table 7. RDE and RPE for PM_{10} at urban background sites with hourly time-resolution.

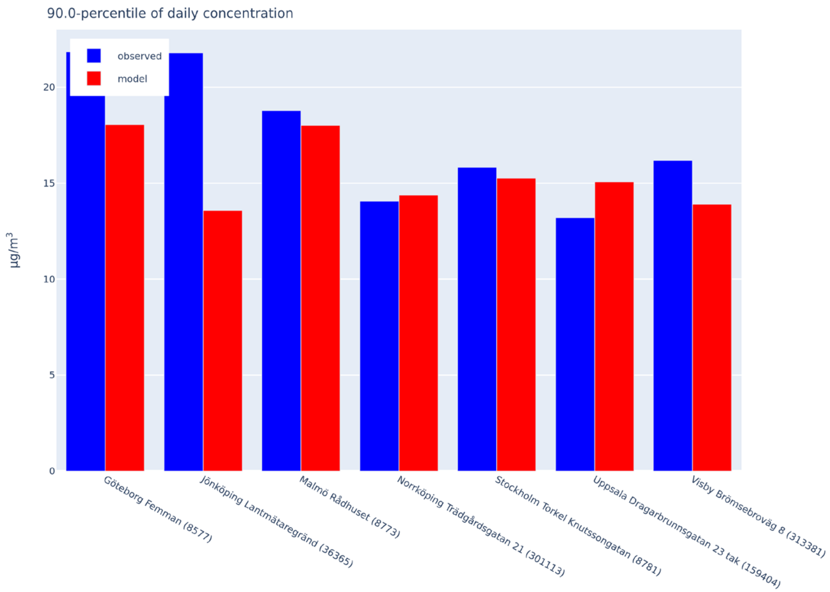


Figure 39. Modelled and observed PM_{10} 90^{th} percentile at urban background sites. This is the current daily limit value at 50 µg/m3. Observed (blue bars) and modelled (red bars).

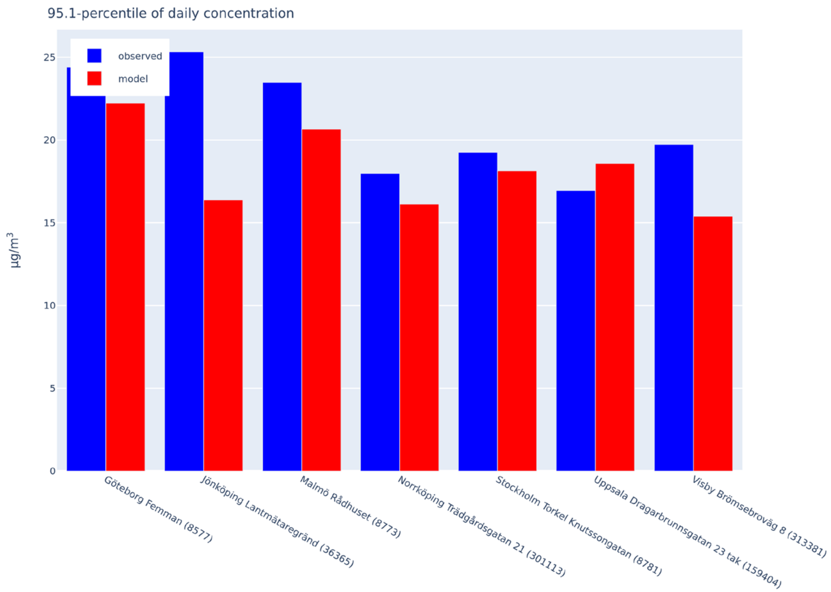


Figure 40. Modelled and observed PM_{10} 95.1^{th} percentile at urban background sites. This is the new daily limit value at 45 µg/m^3 proposed in the revised EU Ambient Air Quality Directive. Observed (blue bars) and modelled (red bars).

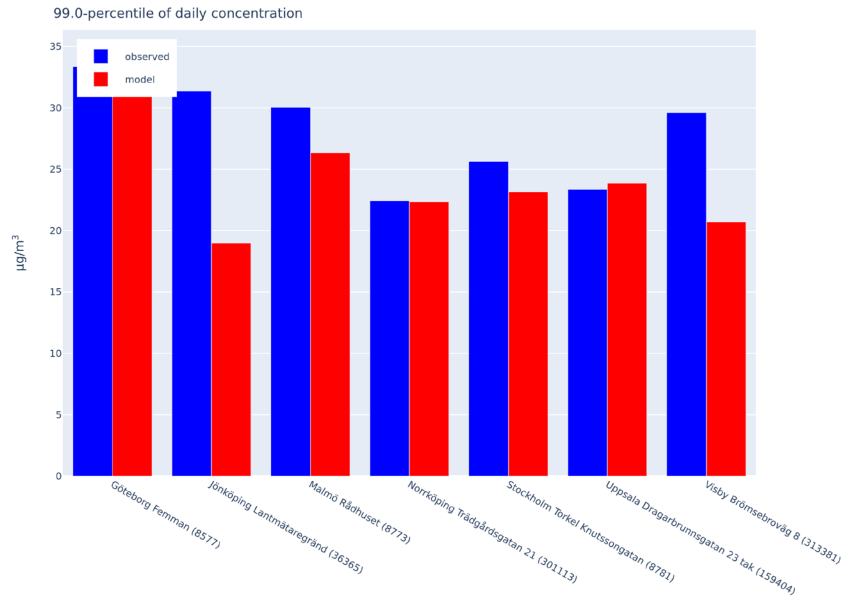


Figure 41. Modelled and observed PM_{10} 99^{th} percentile at urban back-ground sites. This is the daily limit value at 45 µg/m^3 from the World Health Organisation. Observed (blue bars), modelled (red bars) and mod-elled values adjusted against urban background measurements (black bars).

D. Results for PM_{10} at local traffic stations

Traffic Sites	RDE Annual mean	RDE Daily 90 perc	RPE Daily 90 perc
Helsingborg Drottninggatan	0.05	0.15	0.14
Umeå Västra Esplanaden	0.09	0.59	0.67
Uppsala Kungsgatan 67	0.09	0.21	0.29
Stockholm St Eriksgatan 83	0.08	0.15	0.21
Stockholm E4 Skonertvägen	0.03	0.23	0.09
Sollentuna Danderydsvägen	0.03	0.32	0.19
Stockholm Folkungagatan 70	0.04	0.27	0.25
Hedemora Gussarvsgatan	0.11	0.48	0.39
Växjö Liedbergsgatan 11	0.13	1.62	0.12
Östersund Rådhusgatan	0.25	0.26	0.46
Kalmar Södra Vägen	0.06	0.35	0.34
Sollentuna E4 Häggvik	0.03	0.10	0.08
Södertälje Turingegatan 26	0.05	0.18	0.08
Göteborg Övre Husargatan	0.02	0.11	0.11
Sollentuna Sollentunavägen 192	0.05	0.43	0.38
Norrköping Kungsgatan 32	0.02	0.20	0.12
Sundbyberg Tulegatan 9	0.05	0.45	0.28
Örnsköldsvik Centralesplanaden – Nygatan 24	0.02	0.04	0.22
Piteå Prästgårdsgatan	0.26	0.63	0.58
Sundsvall Köpmangatan	0.12	0.32	0.30
Gävle Staketgatan 22	0.03	0.11	0.09
Linköping Hamngatan 10	0.11	0.52	0.41
Västerås Stora Gatan 78	0.24	0.55	0.54
Piteå Hamnplan	0.21	0.53	0.49
Botkyrka Kumla gårdsväg	0.03	0.14	0.04
Härnösand Storgatan	0.09	0.30	0.30
Lund Trollebergsvägen	0.01	0.04	0.06
Stockholm Sveavägen 59 Gata	0.04	0.09	0.10
Stockholm Hornsgatan 108 Gata	0.12	0.37	0.33
Malmö Dalaplan	0.02	0.01	0.03
Sundsvall Bergsgatan	0.03	0.26	0.14
Max value	0.26	1.62	0.67

Table 8. RPE and RDE for PM_{10} annual mean and percentile at traffic stations with hourly time-resolution.

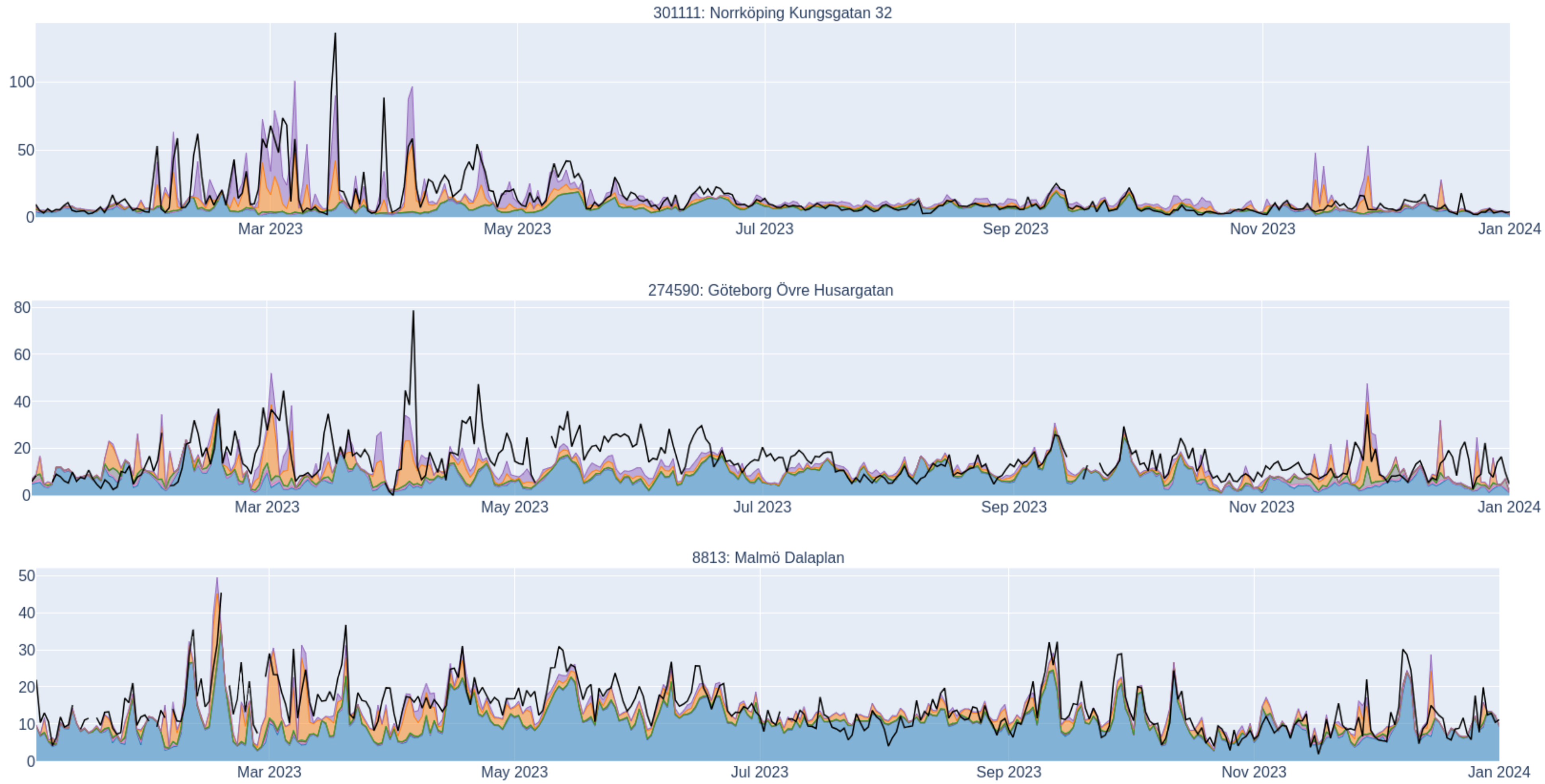
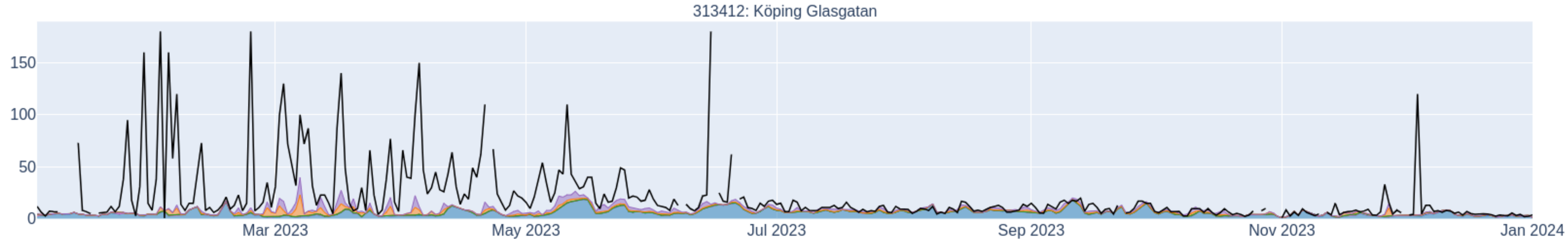
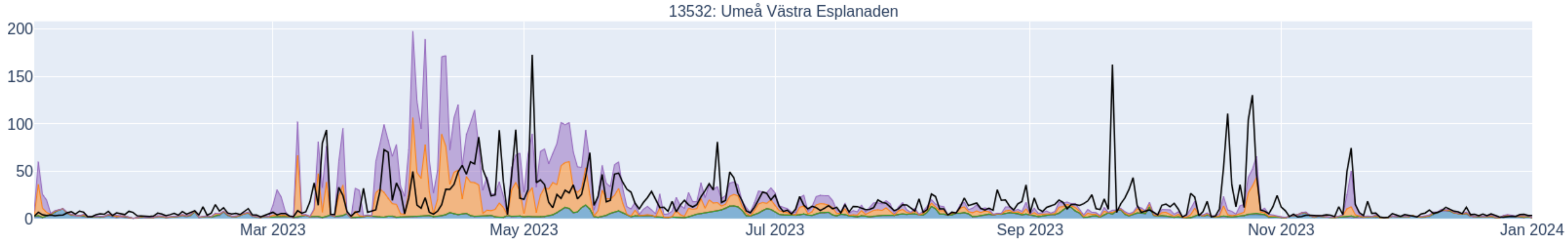
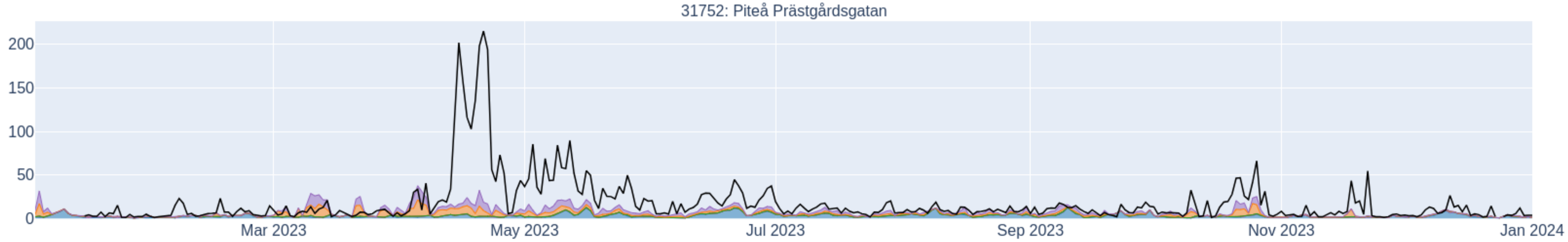


Figure 42. Modelled and observed (black line) daily time-series concentrations of PM_{10} at traffic sites in Norrköping (a), Göteborg (b) and Malmö (c). Modelled concentrations show the contributions from regional (blue area), urban traffic (green area), urban resuspension (yellow area) and street canyons (purple). Concentration unit on y-axis is µg/m^3.

Figure 43. Modelled and observed (black line) daily time-series concentrations of PM_{10} at traffic sites in Östersund (a), Stockholm (b) and Uppsala (c). Modelled concentrations show the contributions from regional (blue area), urban traffic (green area), urban resuspension (yellow area) and street canyons (purple). Concentration unit on y-axis is µg/m^3.


313412: Köping Glasgatan
150
100
50
0
Mar 2023
May 2023
Jul 2023
Sep 2023
Nov 2023
Jan 2024


13532: Umeå Västra Esplanaden
200
150
100
50
0
Mar 2023
May 2023
Jul 2023
Sep 2023
Nov 2023
Jan 2024


31752: Piteå Prästgårdsgatan
200
150
100
50
0
Mar 2023
May 2023
Jul 2023
Sep 2023
Nov 2023
Jan 2024

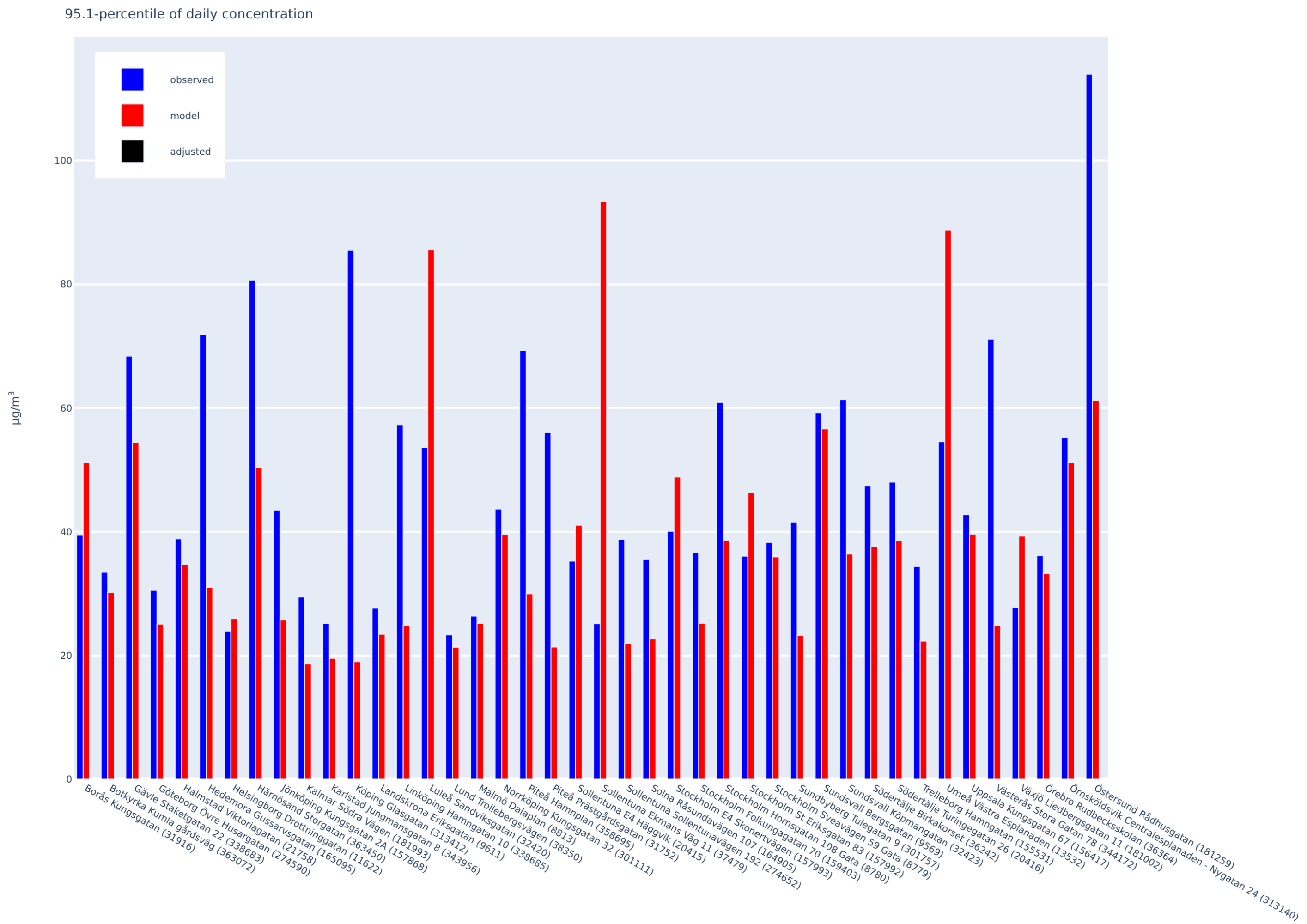


Figure 44. Modelled and observed PM_{10} 95.1th percentile at local traffic sites. This is the new daily limit value at 45 µg/m³ proposed in the revised EU Ambient Air Quality Directive. Observed (blue bars), modelled (red bars) and modelled values adjusted against urban background measurements.

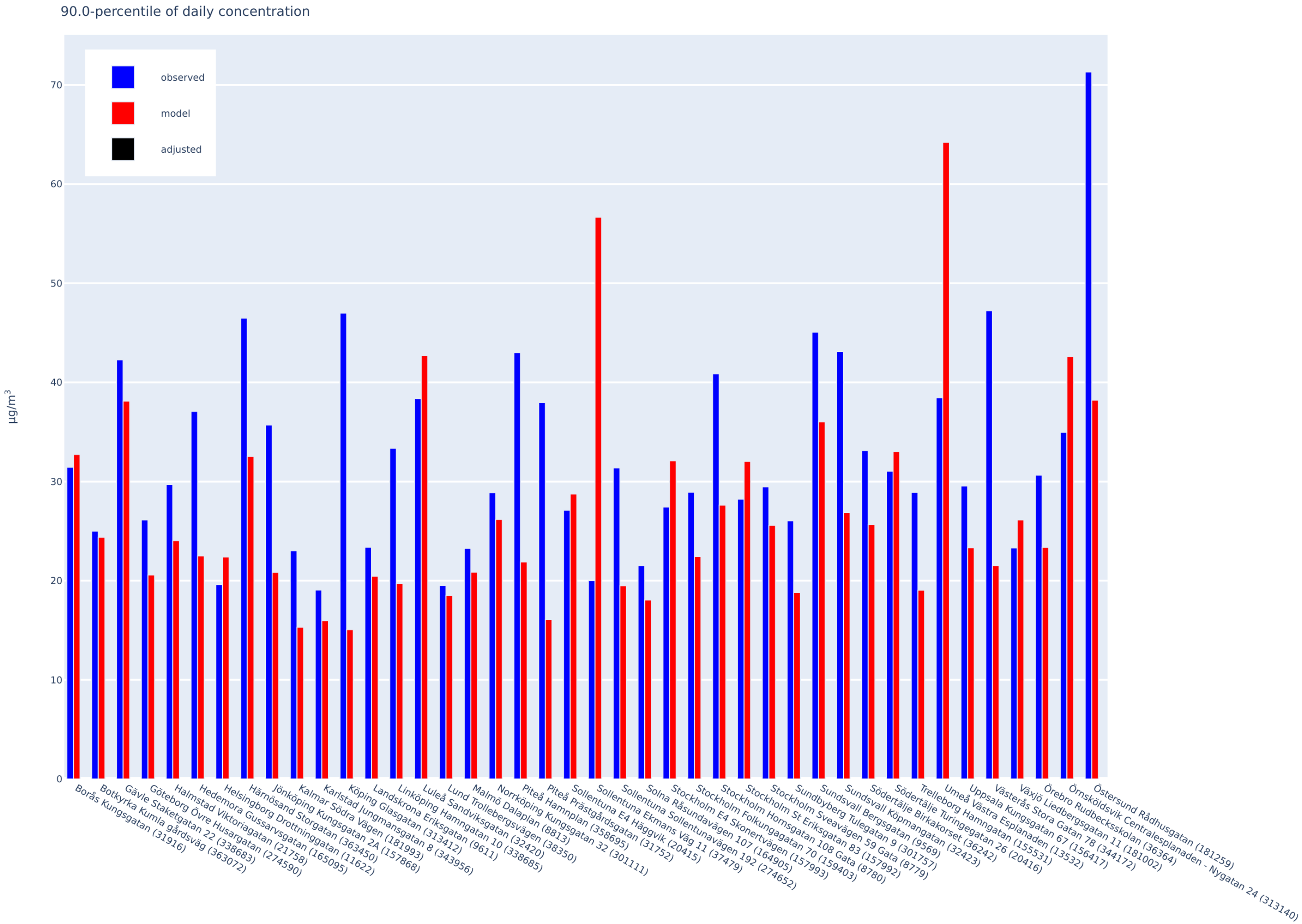


Figure 45. Modelled and observed PM_{10} 90^{th} percentile at local traffic sites. This is the current daily limit value at 50 µg/m³ in Sweden. Observed (blue bars), modelled (red bars) and modelled values adjusted against urban background measurements (black bars).

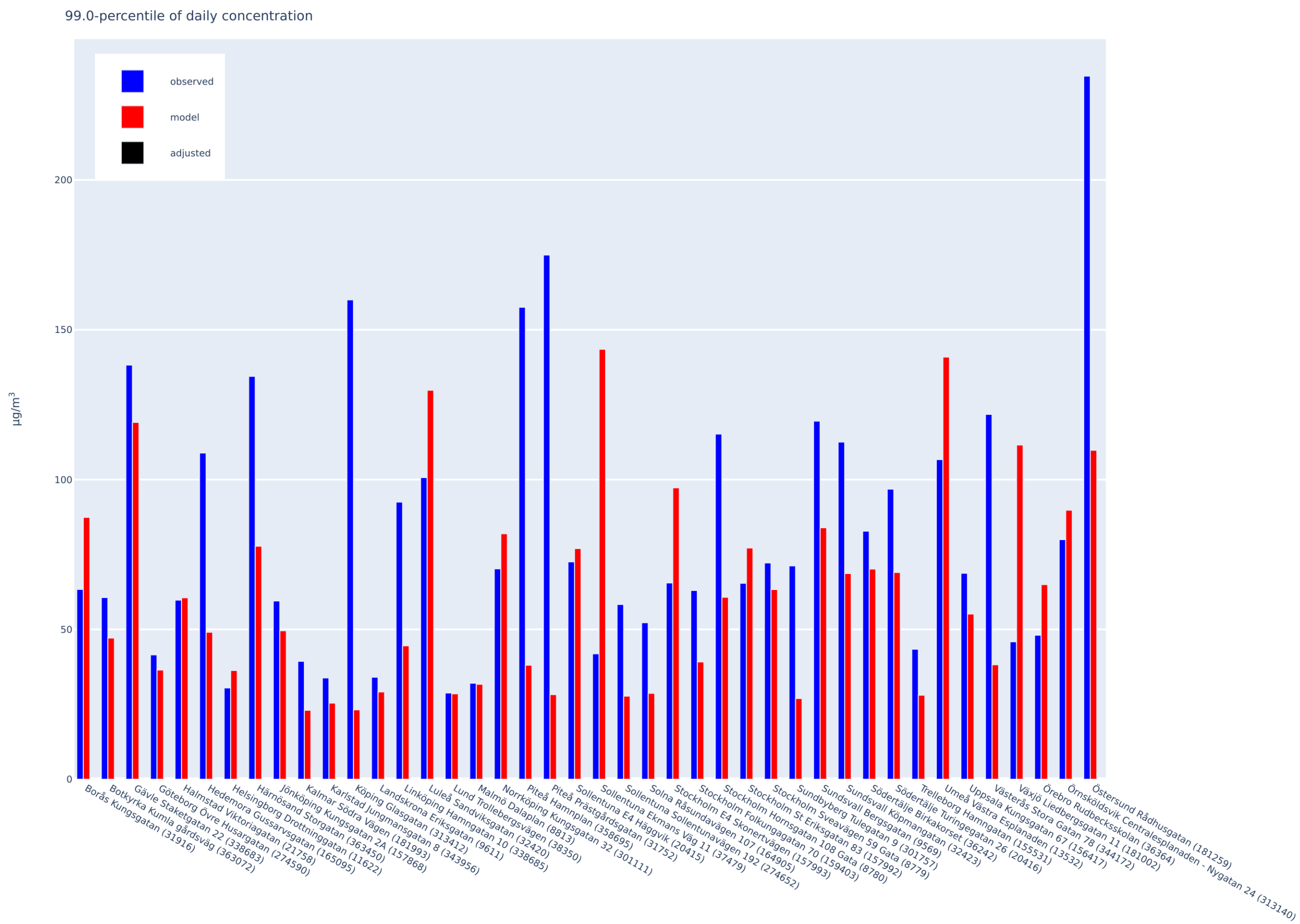


Figure 46. Modelled and observed PM_{10} 99th percentile at local traffic sites. This is the daily limit value at 45 µg/m³ from the World Health Organisation. Observed (blue bars), modelled (red bars) and modelled values adjusted against urban background measurements (black bars).

E. Results for $PM_{2.5}$ at urban stations

Urban background site	RDE Annual mean
Uppsala Dragarbrunnsgatan 23 tak	0.03
Norrköping Trädgårdsgatan 21	0.04
Visby Brömsebroväg 8	0.01
Göteborg Femman	0.06
Malmö Rådhuset	0.00
Stockholm Torkel Knutssongatan	0.01
Max value	0.06

Table 9. RDE and RPE for the annual mean of $PM_{2.5}$ at urban background stations with hourly time-resolution.

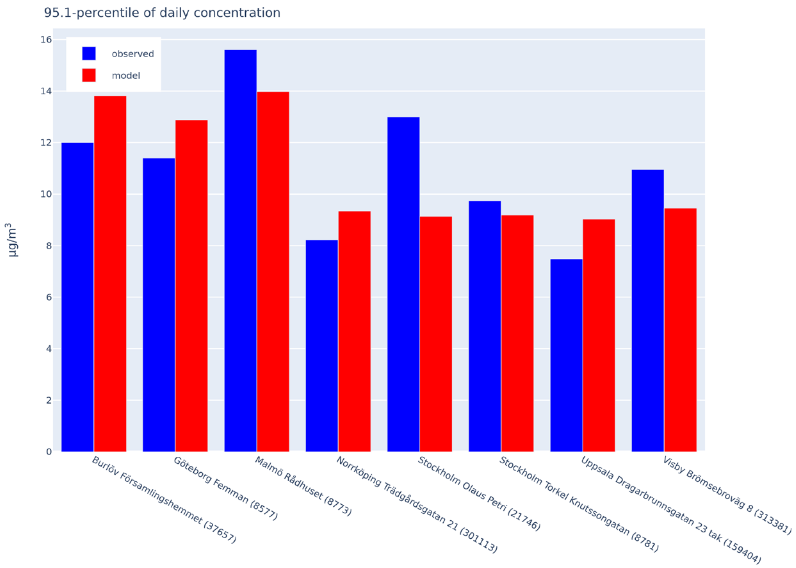


Figure 47. Modelled and observed $PM_{2.5}$ 95.1th percentile at urban background sites. This is the new daily limit value at 25 µg/m3 proposed in the revised EU Ambient Air Quality Directive. Observed (blue bars) and modelled (red bars).

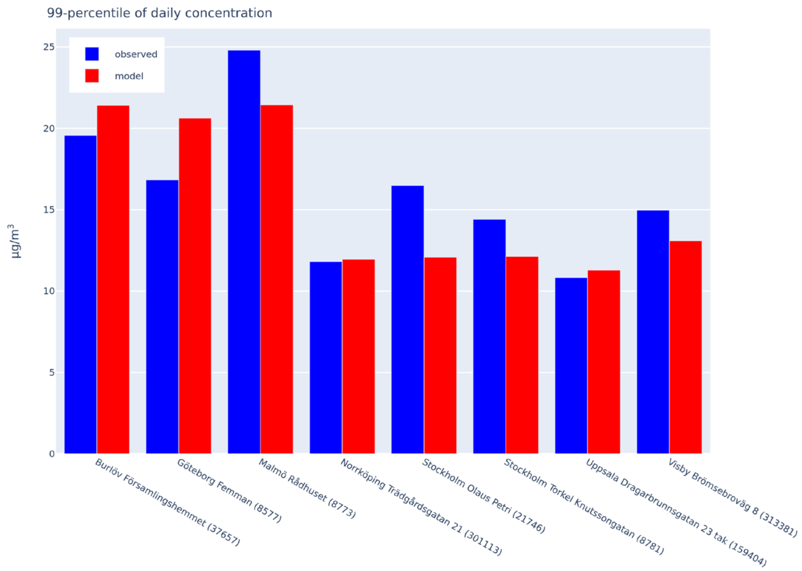


Figure 48. Modelled and observed $PM_{2.5}$ 99^{th} percentile at urban background sites. This is the daily limit value at 15 µg/m^3 from the World Health Organisation. Observed (blue bars) and modelled (red bars).

F. Results for $PM_{2.5}$ at local traffic stations

Traffic sites	RDE Annual mean
Helsingborg Drottninggatan	0.02
Umeå Västra Esplanaden	0.11
Uppsala Kungsgatan 67	0.00
Stockholm St Eriksgatan 83	0.03
Sollentuna Danderydsvägen	0.00
Solna Råsundavägen 107	0.00
Hedemora Gussarvsgatan	0.02
Växjö Liedbergsgatan 11	0.00
Östersund Rådhusgatan	0.01
Kalmar Södra Vägen	0.04
Sollentuna E4 Häggvik	0.00
Sollentuna Sollentunavägen 192	0.00
Norrköping Kungsgatan 32	0.01
Sundbyberg Tulegatan 9	0.00
Sundsvall Köpmangatan	0.01
Gävle Staketgatan 22	0.00
Linköping Hamngatan 10	0.02
Västerås Stora Gatan 78	0.07
Botkyrka Kumla gårdsväg	0.08
Härnösand Storgatan	0.01
Stockholm Hornsgatan 108 Gata	0.01
Sundsvall Bergsgatan	0.03
Max value	0.11

Table 10. RDE for $PM_{2.5}$ annual mean at traffic stations with hourly time-resolution.

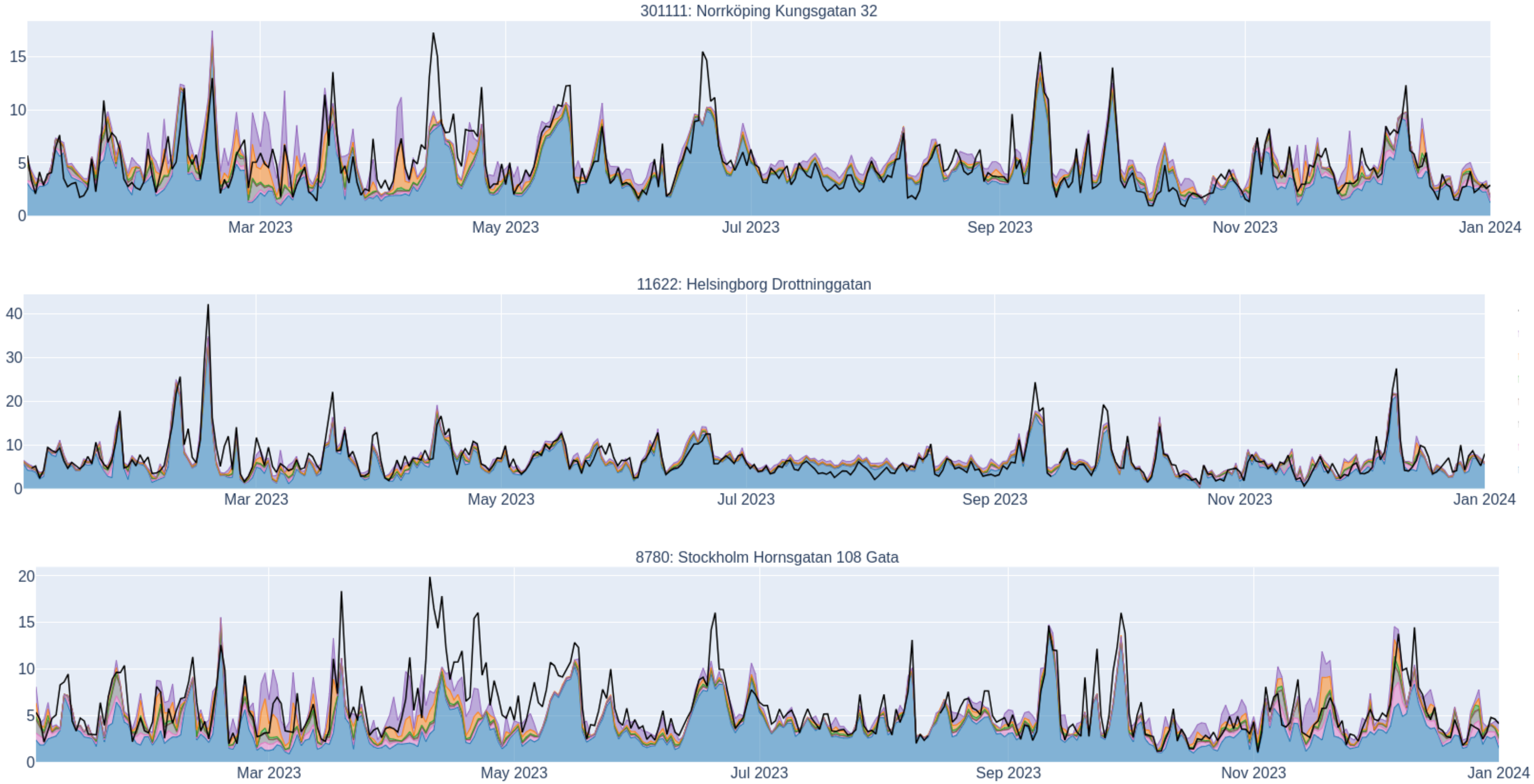


Figure 49. Modelled and observed (black line) daily time-series concentrations of $PM_{2.5}$ at traffic sites in Norrköping (a), Helsingborg (b) and Stockholm (c). Modelled concentrations show the contributions from regional (blue area), urban traffic (green area), urban resuspension (yellow area) and street canyons (purple). Concentration unit on y-axis is $\mu g/m^3$.

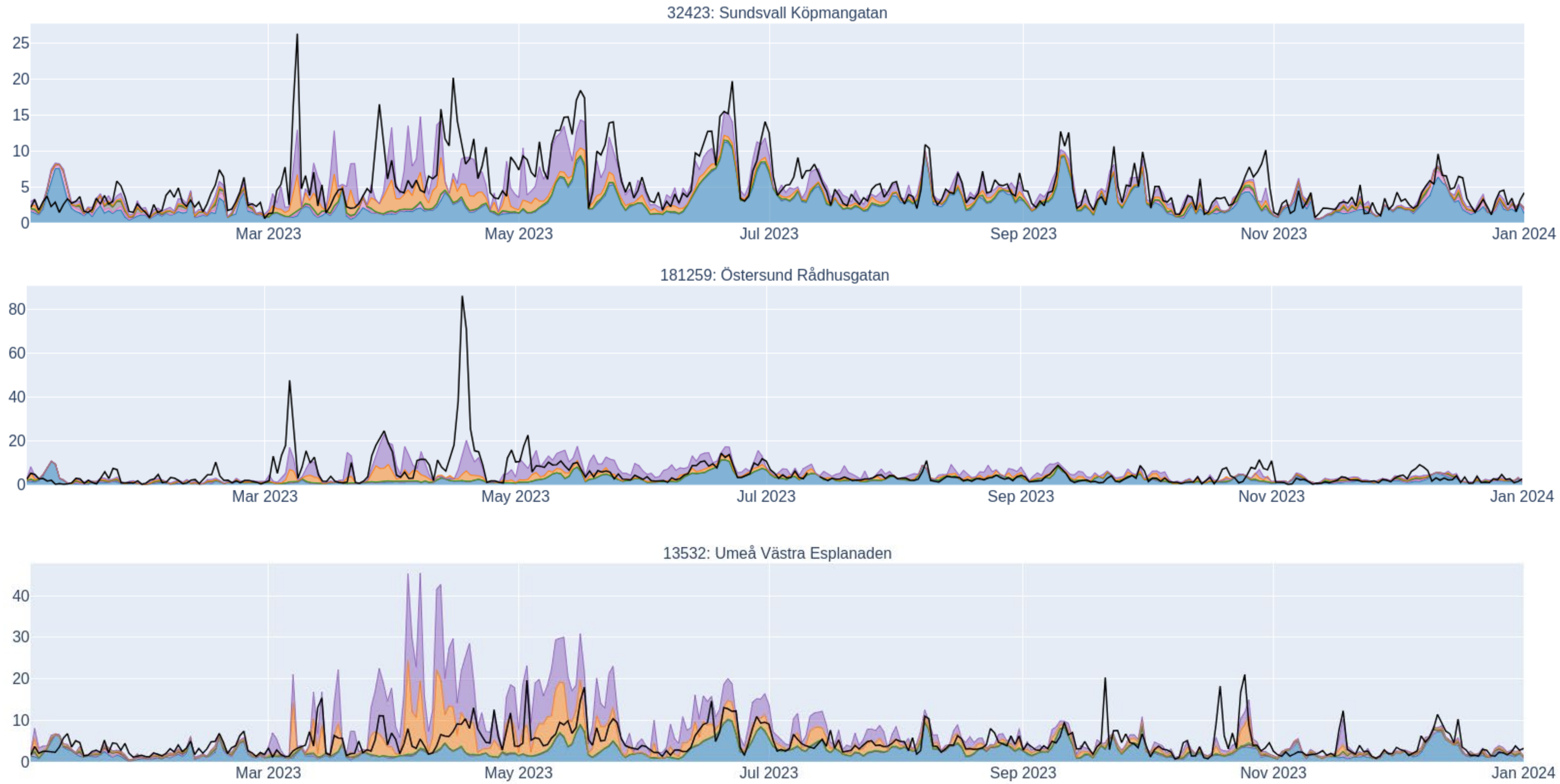


Figure 50. Modelled and observed (black line) daily time-series concentrations of $PM_{2.5}$ at traffic sites in Sundsvall (a), Östersund (b) and Umeå (c). Modelled concentrations show the contributions from regional (blue area), urban traffic (green area), urban resuspension (yellow area) and street canyons (purple). Concentration unit on y-axis is µg/m^3.

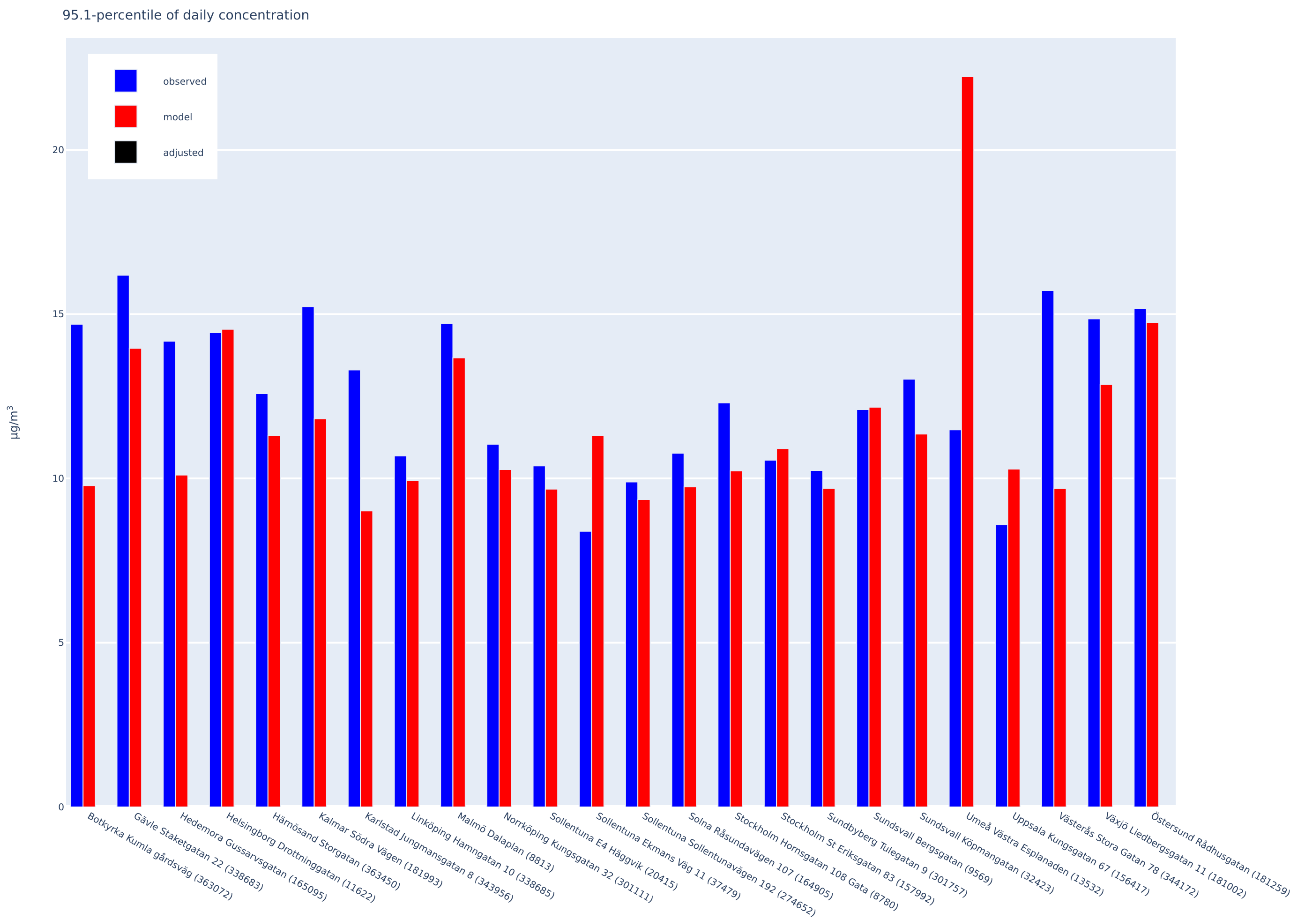


Figure 51. Modelled and observed $PM_{2.5}$ 95.1th percentile at local traffic sites. This is the new daily limit value at 25 µg/m3 proposed in the revised EU Ambient Air Quality Directive. Observed (blue bars), modelled (red bars) and modelled values adjusted against urban background measurements (black bars).

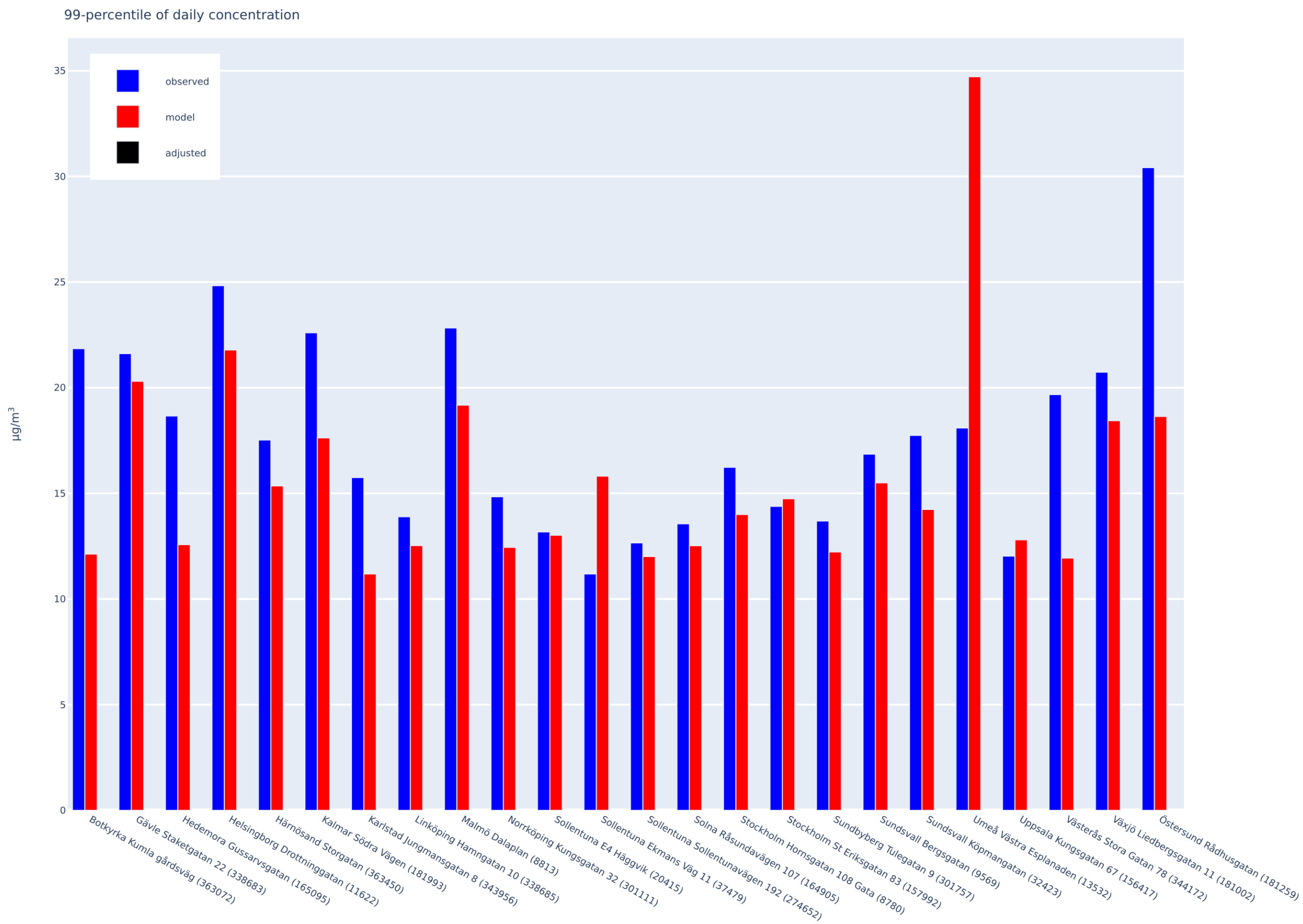


Figure 52. Modelled and observed $PM_{2.5}$ 99th percentile at local traffic sites. This is the daily limit value at 15 µg/m3 from the World Health Organisation. Observed (blue bars), modelled (red bars) and modelled values adjusted against urban background measurements (black bars).

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