



Modelling street level PM₁₀ concentrations across Europe: source apportionment and possible futures

G. Kieseewetter¹, J. Borcken-Kleefeld¹, W. Schöpp¹, C. Heyes¹, P. Thunis², B. Bessagnet³, E. Terrenoire³, H. Fagerli⁴, A. Nyiri⁴, and M. Amann¹

¹International Institute for Applied Systems Analysis (IIASA), Schlossplatz 1, A-2361 Laxenburg, Austria

²Joint Research Centre, Institute for Environment and Sustainability (JRC-IES), Ispra, Italy

³National Institute for Environment and Risks (INERIS), Paris, France

⁴Norwegian Meteorological Institute, Oslo, Norway

Correspondence to: G. Kieseewetter (kiesewet@iiasa.ac.at)

Received: 25 April 2014 – Published in Atmos. Chem. Phys. Discuss.: 10 July 2014

Revised: 18 December 2014 – Accepted: 7 January 2015 – Published: 13 February 2015

Abstract. Despite increasing emission controls, particulate matter (PM) has remained a critical issue for European air quality in recent years. The various sources of PM, both from primary particulate emissions as well as secondary formation from precursor gases, make this a complex problem to tackle. In order to allow for credible predictions of future concentrations under policy assumptions, a modelling approach is needed that considers all chemical processes and spatial dimensions involved, from long-range transport of pollution to local emissions in street canyons. Here we describe a modelling scheme which has been implemented in the GAINS integrated assessment model to assess compliance with PM₁₀ (PM with aerodynamic diameter < 10 µm) limit values at individual air quality monitoring stations reporting to the Air-Base database. The modelling approach relies on a combination of bottom up modelling of emissions, simplified atmospheric chemistry and dispersion calculations, and a traffic increment calculation wherever applicable. At each monitoring station fulfilling a few data coverage criteria, measured concentrations in the base year 2009 are explained to the extent possible and then modelled for the past and future. More than 1850 monitoring stations are covered, including more than 300 traffic stations and 80 % of the stations which exceeded the EU air quality limit values in 2009. As a validation, we compare modelled trends in the period 2000–2008 to observations, which are well reproduced. The modelling scheme is applied here to quantify explicitly source contributions to ambient concentrations at several critical monitoring stations, displaying the differences in spatial origin

and chemical composition of urban roadside PM₁₀ across Europe. Furthermore, we analyse the predicted evolution of PM₁₀ concentrations in the European Union until 2030 under different policy scenarios. Significant improvements in ambient PM₁₀ concentrations are expected assuming successful implementation of already agreed legislation; however, these will not be large enough to ensure attainment of PM₁₀ limit values in hot spot locations such as Southern Poland and major European cities. Remaining issues are largely eliminated in a scenario applying the best available emission control technologies to the maximal technically feasible extent.

1 Introduction

Particulate matter (PM) has become a major concern for public health in recent years (WHO, 2003, 2013). Especially particles with an aerodynamic diameter below 2.5 µm (PM_{2.5}) have been associated with increased mortality mainly due to cardiovascular diseases. The most important sources of primary PM (PPM) emissions include domestic combustion in household heating, road traffic, and industrial combustion. In addition to the emissions of primary particulate matter, particles are also formed in ambient air by chemical and physical processes from precursor gases.

Current European legislation (EU, 2008) states legally binding limit values on ambient concentrations of PM below 10 µm diameter (PM₁₀): daily average PM₁₀ concentrations must not exceed 50 µg m⁻³ for more than 35 days per calen-

dar year, and the annual mean concentration must not exceed $40 \mu\text{g m}^{-3}$. Additional targets exist for PM_{2.5} (for individual monitoring stations as well as for average population exposure), which will enter into force in 2015.

Despite tightening of emission control legislation, EU Member States have been facing severe difficulties to attain these limit values (EEA, 2014). Compliance problems have been widespread and continuous at many locations. As the EU is currently revising its air quality legislation and planning new national emission reduction commitments for 2030, the question arises how compliance will evolve under different policy scenarios.

Assessing compliance with air quality limit values poses a significant new challenge to the modelling framework underpinning policy advice in the EU. Earlier emission control legislation such as the National Emissions Ceilings Directive (EU, 2001) and the Gothenburg Protocol (UNECE, 1999) had a focus on acidification, eutrophication and tropospheric ozone abatement. When assessing compliance of control scenarios with the objectives, e.g. excess of critical loads for acidification, a simulation of pollution concentrations at a small scale, like a street canyon, was not necessary. In the meantime, the focus of interest has shifted to pollutants like NO₂ and PM, which are mostly characterized by urban sources like road traffic, and whose highest concentrations are usually observed in urban areas, particularly along busy roads (Kassomenos et al., 2014; Querol et al., 2004). Therefore, compliance with the policy objectives, i.e. with the limit values for NO₂, PM₁₀ and PM_{2.5}, needs to be checked also at roadside spots.

Consequently, modelling down to urban background scale with a resolution of a few km², as it has been done for the Clean Air for Europe program mid of the last decade, is not sufficient. Modelling tools used for analysing emission control scenarios to tackle PM and NO₂ problems need to resolve also the street canyon scale, to assess to what extent Europe-wide emission control scenarios lead to compliance with the legally binding limit values for ambient PM and NO₂.

Modelling capacities of atmospheric PM have improved strongly in recent years. An overview of the state of the art modelling approaches is given by Rouil and Bessagnet (2013).

The GAINS integrated assessment model (Amann et al., 2011) is employed in the revision of the EU Thematic Strategy on Air Pollution (TSAP) as a policy tool to test the impacts of different pollution control options and calculate least cost solutions for achieving given policy targets (Amann et al., 2013). GAINS calculates particulate matter as the sum of PPM and secondary aerosols caused by anthropogenic emissions of NH₃, SO₂, NO_x, and non-methane volatile organic compounds.

We have recently introduced a downscaling scheme in GAINS to model NO₂ concentrations at different kinds of monitoring stations in the EU, including roadside sta-

tions (Kieseewetter et al., 2014). Here a similar scheme is developed which is now in use to assess future attainment of PM₁₀ limit values in GAINS. In line with the methodology applied for NO₂, we model annual mean concentrations based on past monitoring data. At each air quality monitoring station, measured concentrations in the base year 2009 are disaggregated into contributions from regional background, urban increment, and roadside increment if appropriate. Individual contributions are then subject to the changes in the responsible emissions to calculate concentrations for scenario years.

This paper presents an introduction to the methodology used, a validation of trends against observations, and applications of the model in the context of the revision of the EU air quality legislation. We quantify for several stations with high ambient concentrations the source contributions, pointing out large differences in the composition, and present an estimate of the evolution of PM₁₀ concentrations in Europe until 2030 under different policy assumptions.

The remainder of this article is organised as follows: the modelling scheme is detailed in Sect. 2. A validation of modelled trends against independent observations for the years 2000–2008 is presented in Sect. 3. Uncertainties and shortcomings of the methodology are discussed in Sect. 4. Section 5 presents results: source contributions to different stations are analysed, and the evolution of compliance with limit values in the EU is assessed under different assumptions for the evolution of anthropogenic emissions. Summary and conclusions are given in Sect. 6.

2 Methodology

European legislation states two different limit values for PM₁₀ concentrations (EU, 2008): annual mean concentrations must not exceed a value of $40 \mu\text{g m}^{-3}$, and daily average concentrations must not exceed $50 \mu\text{g m}^{-3}$ for more than 35 days in a calendar year. Out of these two limit values, the limit on daily average concentrations has proven more challenging to attain: e.g. while in 2009 more than 640 monitoring stations did not attain the daily limit value, only about 240 stations reported annual mean concentrations $> 40 \mu\text{g m}^{-3}$ (numbers refer to stations in the EU with more than 80 % data coverage). All of the latter did not attain the daily limit either. Hence, an assessment of future compliance with PM₁₀ standards must focus on the daily limit value.

All calculations in GAINS are done on an annual mean basis and hence cannot address daily exceedances directly. However, a compact linear relation exists between the annual mean and the 36th highest daily average which is decisive for attainment of the daily limit value (see Fig. 1, showing observations from the AirBase¹ database in 2009): a 36th highest daily average of $50 \mu\text{g m}^{-3}$ corresponds to an annual

¹AirBase, the European air quality database. <http://acm.eionet.europa.eu/databases/airbase/>

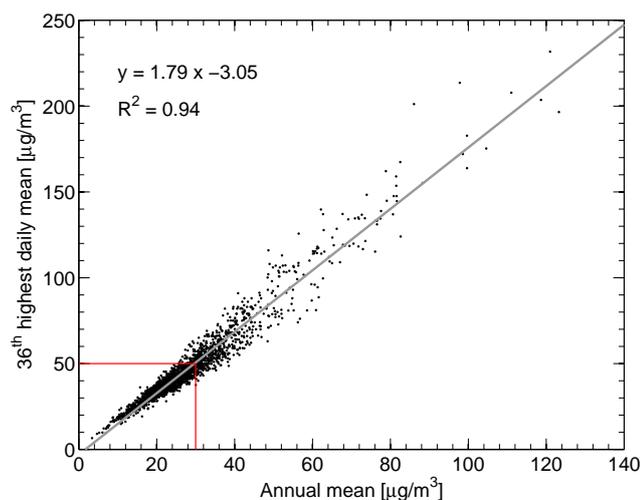


Figure 1. Relation between annual mean concentrations and the 36th highest daily average concentration in AirBase observations (data: all AirBase stations in 2009 with >80 % daily data coverage). The limit on daily exceedances of $50 \mu\text{g m}^{-3}$ is well represented by an annual mean limit of $30 \mu\text{g m}^{-3}$.

mean concentration of $29.6 \mu\text{g m}^{-3}$. In a similar approach, Stedman et al. (2007) used a quadratic relationship between the number of days with PM₁₀ concentrations greater than $50 \mu\text{g m}^{-3}$ and the annual mean to derive an equivalent annual mean concentration of $31.5 \mu\text{g m}^{-3}$. Hence we assess compliance with respect to an equivalent annual mean limit value of $30 \mu\text{g m}^{-3}$. As seen in Fig. 1, within a certain range of annual mean concentrations both compliance and non-compliance with the daily limit value are possible. All stations below $25 \mu\text{g m}^{-3}$ annual mean PM₁₀ comply with the daily mean limit value, above which value the complying fraction decreases steadily. Less than 10 % of stations with annual mean around $35 \mu\text{g m}^{-3}$ are in compliance with the limit on daily average. This range of $\pm 5 \mu\text{g m}^{-3}$ is later used as an uncertainty range around the limit value within which no definite statement on attainment of the daily mean limit value can be made.

The modelling approach is similar to the one laid out by Kiesewetter et al. (2014) for NO_x and NO₂. A schematic overview of the modelling approach is shown in Fig. 2. The modelling scheme combines past monitoring data with bottom up emission modelling and a simplified atmospheric chemistry and dispersion calculation. The starting point of all calculations is monitoring data reported to AirBase in 2009. To ensure quality of the data, we consider only stations with more than 80 % temporal coverage of the daily mean data. For any roadside monitoring station that fulfils this requirement, we first identify contributions from the ambient background and local road traffic emissions, and then model each of these contributions individually. The background itself is modelled as the sum of regional background contributions (primary and secondary) from Europe-wide emissions,

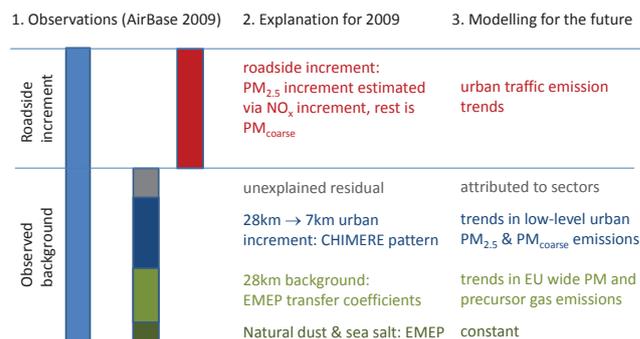


Figure 2. Schematic overview of the PM₁₀ modelling scheme for roadside stations.

an urban increment related to PPM emissions from low-level sources, natural dust, and – if appropriate – a residual regarded as contribution from unknown sources. As a pessimistic assumption, this residual may be left constant in scenario calculations, as done with NO₂ residuals (Kiesewetter et al., 2014); a more realistic treatment attempts an allocation of this residual to natural contributions, regional and local emissions, as detailed below. Differences are only relevant in limited parts of Europe where the bottom up calculated concentrations significantly underestimate observations in 2009.

The following sections provide a description of the methodology for modelling the different contributions to the background (Sect. 2.1), and the roadside increment (Sect. 2.2). The synthesis of the different steps is described in Sect. 2.3.

2.1 Modelling background concentrations

Bottom up calculation of background concentrations is done in two steps, a coarse resolution transfer calculation and a fine scale increment relying on local emissions. All steps described here are done for PM₁₀ and PM_{2.5} independently; however, as the focus of this article is on PM₁₀ we do not mention PM_{2.5} explicitly here. Regional background concentrations are calculated from linear transfer coefficients at a resolution of $0.5^\circ(\text{long}) \times 0.25^\circ(\text{lat})$ or roughly $28 \text{ km} \times 28 \text{ km}$, based on sensitivity calculations with the EMEP chemistry transport model (CTM) (Simpson et al., 2012). The EMEP model contains secondary inorganic as well as organic aerosol formation and calculates PM₁₀ concentrations from the source pollutants primary PM (PPM₁₀), NH₃, NO_x, SO₂, and non-methane volatile organic compounds. In order to match the expected situation best, expected emissions for the year 2020 under current legislation were used as base case for the EMEP model calculations. In each of the sensitivity runs, country total emissions of one pollutant p from one source region r were reduced by 15 % to calculate linear transfer coefficients $\pi(i, p, r)$ from r to each grid cell i ,

$$\pi(i, p, r) = \frac{[\text{PM}_{10}]_{\text{base}}(i) - [\text{PM}_{10}]_{\text{red}}(i)}{0.15 E_{\text{base}}(p, r)} \quad (1)$$

with $E(p, r)$ denoting country total emissions of pollutant p in region r and the subscripts _{base} and _{red} referring to the model run with full 2020 emissions and that with reduced emissions, respectively. Fifty-seven source regions are included, covering Europe and the surrounding sea regions, as described by Kieseewetter et al. (2014).

PM₁₀ concentrations for each EMEP grid cell i are then calculated as the sums of contributions from all source regions r and pollutants p ,

$$\text{PM}_{10}(i) = \delta_{\text{PM}_{10}} + \sum_{r=1}^{57} \sum_{p \in \{\text{P,A,N,S,V}\}} \pi(i, p, r) \cdot E(p, r) \quad (2)$$

with P, A, N, S, V denoting the source pollutants PPM₁₀ (“P”), NH₃ (“A”), NO_x (“N”), SO₂ (“S”), VOC (“V”). $\delta_{\text{PM}_{10}}$ denotes the residual resulting from non-linearities in the system and boundary conditions; it is calculated as the difference between the sum of linear contributions from base case emissions and the base case concentrations modelled with the full EMEP CTM. This model-intrinsic residual is slightly negative in the Po valley, and between 0.5 and 2 $\mu\text{g m}^{-3}$ in the rest of Europe.

The linear approach does not take into account the cross-dependencies between different precursors for secondary inorganic aerosol formation; in particular, it does not explicitly calculate an equilibrium state between ammonium sulphate and ammonium nitrate formation but assumes that the modelled effects of reducing one pollutant by 15 % can be extrapolated linearly. It is clear that this approach has its limitations, in particular if emission changes are unbalanced between different precursors. Modelled concentrations are credible as long as changes in the three precursor gases are similar.

The $0.5^\circ \times 0.25^\circ$ resolution of the linear transfer coefficients is not sufficient to calculate realistic urban background PM concentrations. Kieseewetter et al. (2014) used a full year simulation performed with the CHIMERE chemistry transport model (Menut et al., 2013) with a grid resolution of 0.125° (long) \times 0.0625° (lat) or roughly $7 \text{ km} \times 7 \text{ km}$ to calculate for NO_x a sub-grid increment to the urban background level. Here we use the same simulation to derive an urban concentration increment for PM₁₀. As the formation of secondary PM takes place on timescales of hours, the urban increment is calculated as a function of PPM emissions². For the CHIMERE model runs used here, Cuvelier et al. (2013) showed that most of the concentration increment from the $28 \text{ km} \times 28 \text{ km}$ to the $7 \text{ km} \times 7 \text{ km}$ resolution is explained by emissions of PPM. This approach is used here to calculate a regression coefficient ξ relating increments in the

²The assumption that secondary PM formation can be neglected at the local scale is a simplification. E.g., Lenschow et al. (2001) reported that local nitrate formation accounts for about 4 % of total PM₁₀ in Berlin, and this fraction is missed or misattributed to PPM in the model.

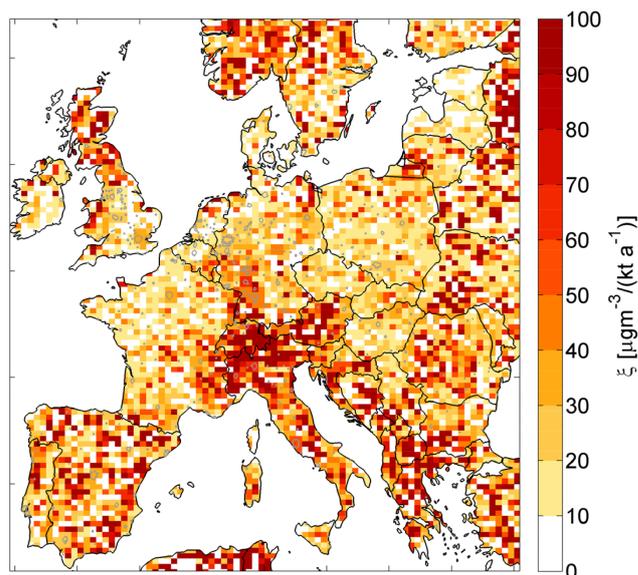


Figure 3. The regression coefficient ξ relating additional primary PM emissions within each EMEP grid cell to PM concentration increments.

PM₁₀ concentration to emissions of primary PM₁₀ in the lowest atmospheric layer, so that in a sub-grid cell m of the $28 \text{ km} \times 28 \text{ km}$ grid cell i the PM₁₀ concentration is calculated as

$$[\text{PM}_{10}](m) = [\text{PM}_{10}](i(m)) + \xi(i(m)) \times \{e_L(m) - e_L(i(m))\} \quad (3)$$

with $e_L(m)$ the low level (traffic and household) emissions in m and $e_L(i(m))$ the same averaged over the corresponding EMEP grid cell i . The parameter ξ relates the pattern of concentration increments to the pattern of PPM emissions.

ξ depends largely on the meteorological characteristics of the area in question. Although calculated only for 2009, ξ introduces a parameterization of the urban increment with low level emissions that can easily be transferred to different scenario years. Since this resolution-dependent concentration increment is relevant mostly in urban areas, we refer to it also as urban increment, although it is calculated for every EMEP grid cell regardless of its location and may also be negative in sub-urban grid cells. EMEP grid cells containing parts of the same urban area are combined in the regression analysis, enhancing the statistical significance of the calculation. Each major city is thus assigned a single characteristic value of ξ .

A map of ξ for the whole domain of the CHIMERE model is shown in Fig. 3. Large differences are visible between different regions owing to the different orography and local meteorological conditions that influence boundary layer mixing. Particularly, the effect of low wind speed and frequent inversion layers is visible in Alpine regions and the Po val-

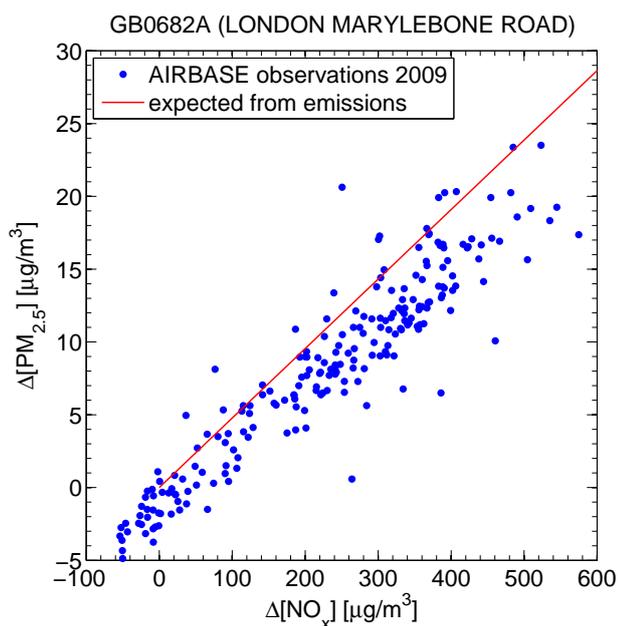


Figure 4. Roadside increments of NO_x and PM₁₀ at Marylebone Road monitoring site, London: daily mean AirBase observations in 2009.

ley, whereas the higher wind speeds lead to correspondingly lower ξ values close to the Atlantic or North Sea shorelines.

R^2 values for the regression used in ξ calculation are high especially in major urban areas with significant PM emissions. Major European cities like Paris, London, Berlin, Madrid show values around 0.9 or higher.

While the urban background in large urban areas is represented well by the 7 km \times 7 km concentrations, concentrations in smaller cities are underestimated as the CHIMERE grid cells are not small enough to capture inner city concentrations. Adopting the methodology described by Kiesewetter et al. (2014), we use population density on a 0.01° \times 0.01° grid (\sim 0.75 km (long) \times 1.1 km (lat) resolution) to redistribute domestic and light duty vehicle emissions and apply Eq. (3) to inner urban emission densities for 376 European cities with more than 100 000 inhabitants.

2.2 Modelling the traffic increment

Roadside concentrations of PM are typically a few $\mu\text{g m}^{-3}$ higher than concentrations in ambient urban background air (around $5 \mu\text{g m}^{-3}$ on the European average, see Fig. 6, but with a large spread); the difference originates from traffic related emissions of particles in the street canyon itself. We define the PM₁₀ roadside increment as

$$\Delta[\text{PM}_{10}] = [\text{PM}_{10}]_{\text{road}} - [\text{PM}_{10}]_{\text{B}} \quad (4)$$

with $[\text{PM}_{10}]_{\text{road}}$ and $[\text{PM}_{10}]_{\text{B}}$ the roadside and urban background concentrations of PM₁₀ (equivalently for fractions of PM₁₀ or other tracers).

On timescales relevant for the mixing of air within street canyons, secondary particle formation can be neglected. Traffic related PM originates not only from combustion processes, but contains also a significant fraction of non-exhaust emissions from brake and tyre wear, road surface abrasion, and resuspension of road dust (Thorpe and Harrison, 2008).

The coarse fraction of PM ($\text{PM}_{\text{coarse}} = \text{PM}_{2.5-10} = \text{PM}_{10} - \text{PM}_{2.5}$) has been found to consist almost entirely of non-exhaust particles (Harrison et al., 2012), and at the same time is more affected by resuspension as it may accumulate on the road surface. Between different regions, large differences exist in the size partitioning and thus exhaust or non-exhaust origin of the PM₁₀ roadside increment: in London, Harrison et al. (2001) determined a roughly even split of the roadside increment in PM_{2.5} and PM_{coarse}, while in Nordic countries the coarse fraction dominates, caused by the widespread use of studded tires and application of traction sanding in winter (Kupiainen et al., 2005; Gustafsson et al., 2009).

As both the sources and the dispersion behaviour of fine and coarse traffic related PM are different, fine and coarse fractions are treated individually in the traffic increment calculation. Only few monitoring sites in Europe enable a distinction of fine and coarse roadside increment from observations. Thus, in our model the components are estimated via a correlation with the NO_x roadside increment, of which measurements are widely available.

The approach followed here distinguishes and idealises the fine and coarse fractions of PM. We assume that primary PM_{2.5} is dispersed like NO_x, which is chemically inert at the timescales involved, while PM_{coarse} is subject to accumulation and resuspension. The activity that causes the concentration increments in NO_x and PM_{2.5} is the same (namely vehicular emission in the street canyon in question), hence we can write

$$\Delta[\text{PM}_{2.5}] = \Delta[\text{NO}_x] \cdot \frac{E_{\text{PM}_{2.5}}}{E_{\text{NO}_x}} \quad (5)$$

with $E_{\text{PM}_{2.5}}$ and E_{NO_x} the national total emissions of each pollutant from road traffic. Due to the lack of station specific data we assume that the fleet composition at any station is well represented by the national average for urban conditions. A similar concept has been used by Boulter et al. (2006) for estimating the resuspension contribution to the roadside PM increment. Figure 4 shows this relation for Marylebone Road traffic station in London, using AirBase daily observations for the year 2009. Some roadside stations also show good correlation between $\Delta[\text{NO}_x]$ and $\Delta[\text{PM}_{10}]$; however, we do not use this relation but focus on the fine fraction here. To avoid unrealistically large PM_{2.5} roadside increments in case of observational errors, the fine fraction is limited to 90 % of the total PM₁₀ increment in the base year.

The coarse fraction of the traffic increment is then estimated as the residual

$$\Delta[\text{PM}_{\text{coarse}}] = [\text{PM}_{10}]_{\text{road}}^{\text{obs}} - [\text{PM}_{10}]_{\text{B}}^{\text{obs}} - \Delta[\text{PM}_{2.5}] \quad (6)$$

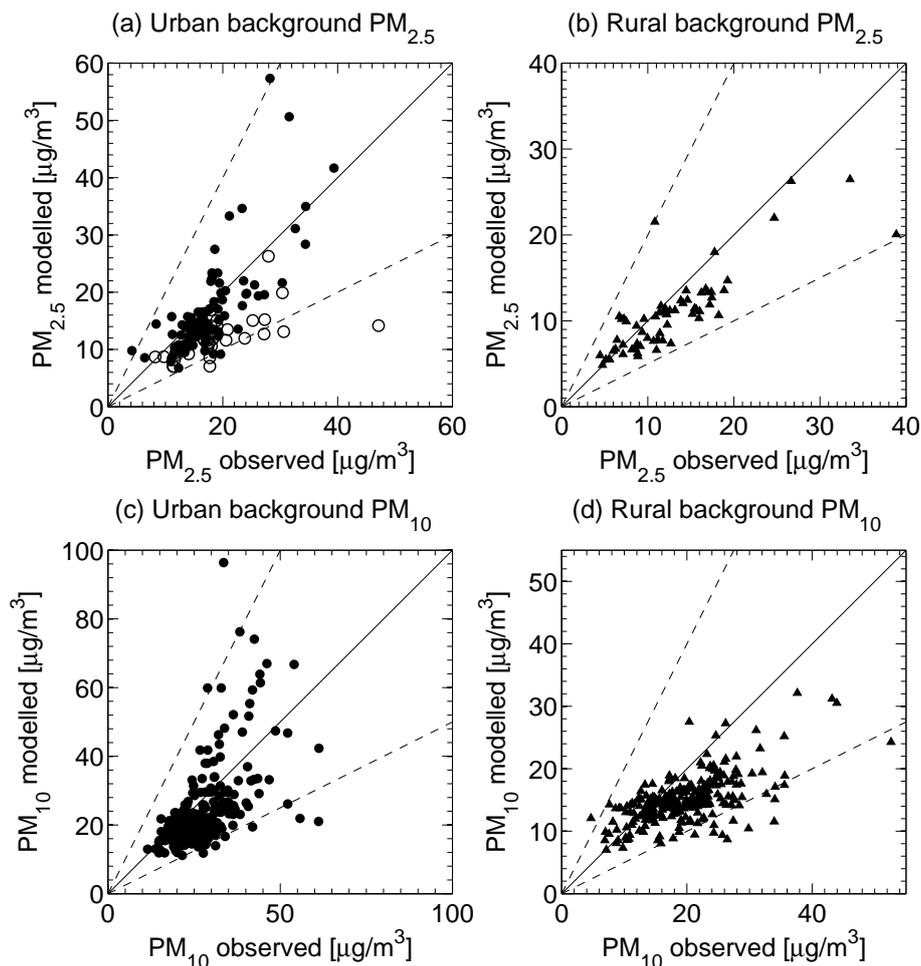


Figure 5. Bottom up calculated vs. observed PM_{2.5} and PM₁₀ concentrations at urban and rural background monitoring stations in 2009. Panel (a) distinguishes into stations located in cities > 100 000 inhabitants (dots) and those not (circles). For better viewing, only urban stations in cities > 100 000 inhabitants are shown for PM₁₀ (c).

with $[PM_{10}]_B^{obs}$ and $[PM_{10}]_{road}^{obs}$ the observed background and roadside concentrations, respectively.

Once the fine and coarse fractions of the roadside increment are estimated for the base year, each of them is scaled individually with the appropriate trend in urban PM_{2.5} or PM_{coarse} road traffic emissions (exhaust + non-exhaust). The trend in PM_{coarse} traffic emissions is essentially proportional to the trend in traffic volume as these non-exhaust emissions are not controlled on a large scale so far. As the PM_{coarse} roadside increment contains a significant fraction of re-suspended dust, the assumption that concentrations scale proportional to emissions may be too pessimistic, as the additional contribution of a single vehicle to dust resuspension decreases with total traffic volume (Boulter, 2005).

Wherever possible, the same background stations are used for PM₁₀ and NO_x in the roadside increment calculation. Provided that sufficient temporal overlap exists (> 75 % of all days in 2009), $\Delta[PM_{10}]$ and $\Delta[NO_x]$ are calculated as annual averages over all days when NO_x and PM₁₀ roadside

and background stations provide data. If station pairs are not available, NO_x and PM₁₀ background are calculated independently; if for a station pair sufficient overlap period is not available, $\Delta[PM_{10}]$ and $\Delta[NO_x]$ are calculated without temporal synchronisation.

2.3 Combination of the different modelling steps

The different modelling steps are combined as indicated in Fig. 2. Model calculations are possible for every station in the AirBase database which fulfils a few data coverage criteria: for background stations, all stations with more than 80 % coverage of daily mean PM₁₀ concentration data are included. For roadside stations, in addition NO_x data are required for the same station, and at least one suitable PM₁₀ and one NO_x background station, ideally identical, are needed. All of these stations must fulfil the 80 % temporal coverage criterion. With these criteria, a total of around 1 870 PM₁₀ stations are covered by the model, of which 316

are traffic stations and 492 did not attain the equivalent limit value as defined in Sect. 2 in 2009 (315 if contributions from natural dust and sea salt are subtracted).

Calculations involve two steps: first, the calculation is done for the base year 2009. For a traffic station, the observed background PM₁₀ is determined as the mean of the observations from all background stations within the same city (according to AirBase meta-information) or within 20 km if the former is not available. Modelled background PM₁₀ is calculated as described in Sect. 2.1 as the sum of 28 × 28 km² background (light green in Fig. 2) and the urban increment from low level PPM emissions within the 28 km grid cell (dark blue), and calculated concentrations of PM₁₀ from natural origin (dark green). GAINS transfer coefficients pertain only to anthropogenic emissions. Suspension and dispersion of natural dust and sea salt are calculated in the EMEP CTM for the year 2009. These natural fields are subtracted from observations before determining the residual between total modelled and observed concentrations. This residual is then attributed to the likely sectors of origin (see below). For a traffic station, the fine and coarse fractions of the observed roadside increment are calculated as described in Sect. 2.2.

As a second step, calculations are done for any scenario year by replacing base year emissions with emissions for the scenario year in question. GAINS calculates emissions bottom up from projections of anthropogenic activity, estimated shares of emission control technologies and appropriate emission factors for each technology (Klimont et al., 2002). GAINS provides emissions typically in five-year intervals extending from 2000 to 2030; for other years emissions are interpolated linearly between these points.

In case of a positive residual in base year background concentrations (negative bias, model under-explaining observations), the residual may be related to natural dust, re-suspension of dust, missing emissions or a missing representation of boundary layer inversions in the EMEP or CHIMERE model simulations. While the unexplained residual is kept constant in the NO₂ scheme (Kiesewetter et al., 2014), this treatment seems too pessimistic for PM₁₀ in some European regions: particularly in Southern Poland, extreme measured concentrations are at some stations not matched by the model. However, both temporal profile as well as geographical distribution of the offsets suggest a clear relation to domestic combustion in winter, indicating that domestic emissions are underestimated in emission inventories, or boundary layer mixing is overestimated in the CTM simulations. Consequently, a simple “best estimate” disaggregation of the residual concentration is undertaken. First, the residual is disaggregated into a regional and a local unexplained component; the regional component is determined as the linear interpolation of unexplained residuals at nearby rural background monitoring stations, while the remainder is by definition caused by local emissions. Within the regional component, natural dust is increased up to a reasonable maximum (the PM₁₀ dust fields used in the CHIMERE

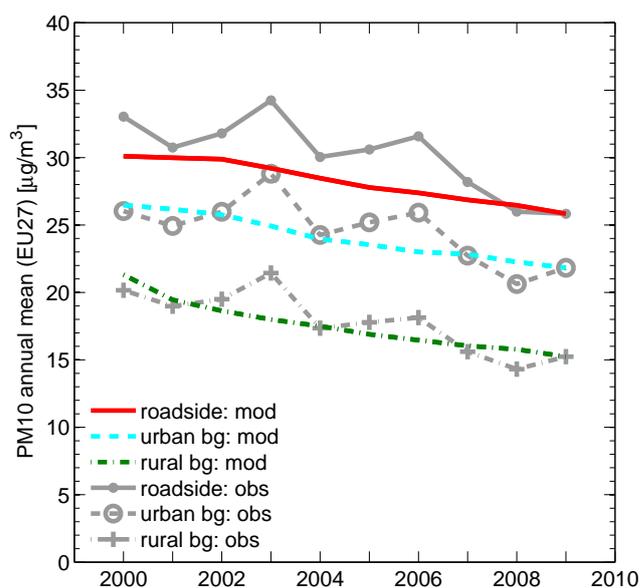


Figure 6. Time series of modelled and observed PM₁₀ averaged across different categories of monitoring stations in the EU.

simulation, which are considerably higher than the EMEP dust fields), and the rest is assumed to be composed like the modelled 28 km × 28 km concentrations at this location. The local residual component, on the other hand, is assumed to be related to an underestimation of local emissions or their enhancement through inversion situations, and are attributed proportionally to the gridded PPM emissions within a radius of 20 km. While this methodology can only provide a rough estimate and takes into account only “known unknowns”, it still seems more realistic than keeping the residual constant.

If the residual is negative (positive bias, model over-explaining observed background), the ratio of observed to calculated background PM₁₀ in the base year is used to scale calculated concentrations in scenario years.

3 Validation

Validating a model which calculates PM concentrations for roughly 1 870 air quality monitoring stations is challenging. Here we show a comparison of bottom up calculated background PM concentrations for various background stations in Europe, and a validation of trends at background and roadside monitoring stations. Since the model is constrained by observations in the base year, validating absolute modelled concentrations at roadside monitoring stations is not possible.

Figure 5 compares PM_{2.5} and PM₁₀ background concentrations from bottom up modelling to observed concentrations at background monitoring stations, for urban and rural background stations separately. This provides a validation of the background calculation methodology from linear trans-

fer coefficients plus downscaling to the urban background level. Each dot in the figure represents the annual mean at one monitoring station. The offset to the 1 : 1 line is compensated in scenario calculations as described in Sect. 2.3. We here use a subset of the model performance indicators proposed by Thunis et al. (2012): absolute bias, normalised mean bias, and correlation coefficient. PM_{2.5} concentrations are generally well modelled with a residual of $-2.5 \mu\text{g m}^{-3}$ (normalised mean bias -15%) remaining on the European average, 94 % of stations between a factor of two margins from the observations. The mean bias decreases to $-0.9 \mu\text{g m}^{-3}$ (-5%) at urban background stations located in cities $> 100\,000$ inhabitants, where urban polygons were defined as described by Kieseewetter et al. (2014) (black dots in Fig. 5(a)). Urban background stations in smaller cities for which urban polygons are not defined (open circles in Fig. 5(a)) have a considerably higher offset of $-6.6 \mu\text{g m}^{-3}$ or a normalised mean bias of -36% . This points to the added value of the last downscaling step beyond the 7 km CHIMERE grid resolution wherever possible, and at the same time supports the re-allocation of local residuals to nearby PPM emissions as described in Sect. 2.3. At rural background stations (Fig. 5(b)) the model has a mean bias of $-1.9 \mu\text{g m}^{-3}$ (-15% normalised mean bias).

The performance of the model is less encouraging for the coarse PM fraction. The spatial variability between stations is underestimated, leading to an average bias of $-6.5 \mu\text{g m}^{-3}$ or 26 % of observed PM₁₀ in the base year (for urban background stations, $-3.2 \mu\text{g m}^{-3}$ or -12% at stations within urban polygons, compared to $-10.8 \mu\text{g m}^{-3}$ or -37% at stations without urban polygons). Correlation coefficients between model and observations are 0.76 and 0.83 for urban background and rural background PM_{2.5}, respectively, and around 0.6 for PM₁₀. Aside from uncertainties in direct anthropogenic emissions of PM or its precursors, offsets partly arise from uncertainties in the natural emissions and effects of re-suspended dust.

For the full PM₁₀ model, since offsets in the base year are compensated, only trends can be validated. Modelled trends in the decade 2000–2009 are compared to observations in Fig. 6. Here, model predictions at different categories of monitoring stations are compared to the annually averaged observations (only stations with at least five years of data are included here).

Different observational methods are applied in different locations. Particularly the use of the tapered element oscillating microbalance (TEOM) causes difficulties in comparing results to the standard gravimetric method as some semi-volatile compounds are lost in the measurement process due to the necessary heating of the sample (e.g. Hauck et al., 2004). Similar difficulties are associated with monitors based on beta ray attenuation. Scaling factors are usually applied to correct for these offsets to the reference method; however, there is no uniform methodology as to how these are calculated across the EU. TEOM measurement data from

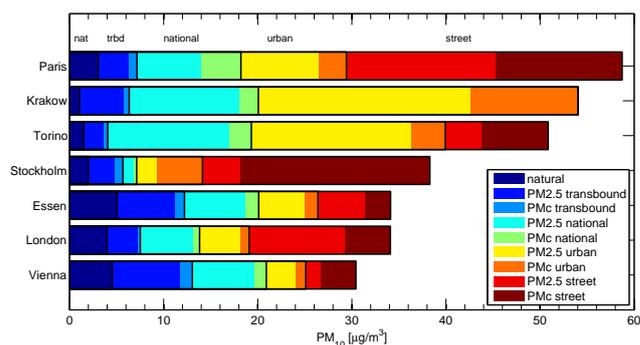


Figure 7. Modelled composition of PM₁₀ at seven monitoring stations with different characteristics in the year 2009: spatial source contributions. “nat”: natural, “trbd”: transboundary.

France exhibit a step increase when a new methodology (adjustments based on TEOM Filter Dynamics Measurement System measurements) was introduced in 2007 to include the semi-volatile components. To establish a consistent time series and foster comparison with other monitoring sites, raw data from French TEOM measurement sites before 2007 were scaled by average correction factors as reported by AIRPARIF (2011a): $+20\%$ for roadside stations and $+30\%$ for background stations.

Trends are well captured by the model: slight declines of around $-0.36 \mu\text{g m}^{-3} \text{ yr}^{-1}$ (urban background), $-0.45 \mu\text{g m}^{-3} \text{ yr}^{-1}$ (traffic), and $-0.48 \mu\text{g m}^{-3} \text{ yr}^{-1}$ (rural background) are seen in the decade 2000–2009. The decline in observed roadside PM₁₀ concentrations is stronger than modelled ($-0.71 \pm 0.20 \mu\text{g m}^{-3} \text{ yr}^{-1}$), which is due to a stronger decline in the roadside increment in observations. This possibly points to successful local measures that have been implemented during this decade in order to reduce exhaust emissions or dust suspension from road traffic at hot spot sites (e.g. local traffic management / low emission zones, dust binding measures in Scandinavian countries, changes in winter road maintenance) and that are not represented in the Europe-wide emission calculation scheme. The conclusion from Fig. 6 is that rural and urban background concentrations are on average modelled well, while the model may be slightly pessimistic for future roadside concentrations.

4 Uncertainties and caveats

The simplifications needed in a Europe-wide modelling of PM down to individual street canyons lead to considerable uncertainty. A general limitation of this modelling approach is that it only provides concentration projections for monitoring stations for which AirBase data are available for 2009 and indeed only for a subset of stations for which the mentioned data criteria have been met. However, these locations are used for assessing compliance with the EU Air Quality

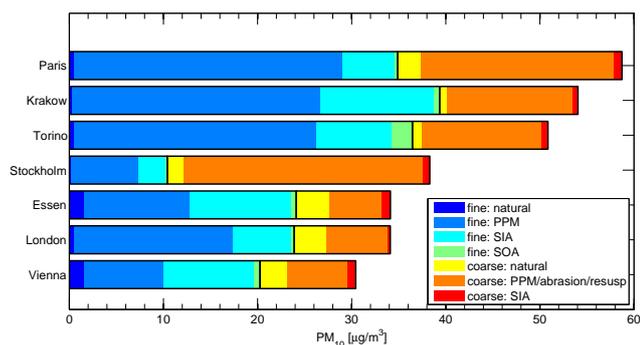


Figure 8. Modelled composition of PM₁₀ at seven monitoring stations with different characteristics in the year 2009: chemical composition.

Directive, and the model covers 80 % of the stations exceeding the limit value in 2009.

Kiesewetter et al. (2014) provided a thorough discussion of the uncertainties associated with the roadside NO₂ calculation scheme which follows a very similar approach. Hence, we only provide here a short discussion of the uncertainties specific to the PM scheme and refer the reader to the cited reference for a more general treatment.

Limitations induced by the linearised approach taken here have been mentioned in Sect. 2.1, and are discussed by Amann et al. (2011).

Considerable uncertainties stem from the emission inventory used for the base year. The emission inventory itself is described by Kiesewetter et al. (2014). Emissions from domestic combustion are uncertain in critical regions such as Southern Poland or Bulgaria, where this sector is believed to be of key importance. Test runs with the CHIMERE CTM revealed that domestic heating emissions in Southern Poland are considerably underestimated in official reports and previous versions of GAINS. Consultations with national experts led to the conclusion that this discrepancy is likely caused by the more widespread use of low quality coal for household heating in coal mining and adjacent areas than previously assumed. As a preliminary solution, domestic combustion emissions from provinces with active coal mines were multiplied by a factor of 8, while those in neighbouring provinces were adjusted by a factor of 4. These adjusted emissions lead to a distinctively better match of modelled with measured PM₁₀ concentrations in Poland.

While such a flat correction factor adjusts the average well, at some monitoring stations a significant unexplained share remains (particularly in small cities, while concentrations in large cities are a bit overestimated). As a worst case scenario this residual may be left constant, as it is not explained by the emission inventory (including adjustments). However, in this case several regions would have little chance of attaining air quality limit values, which seems unrealistic in case of targeted action such as assumed in the policy scenarios.

Therefore, residuals were site-specifically attributed to their likely sources as described in Sect. 2.3; however, the air quality benefits achieved under control scenarios in these regions are subject to considerable uncertainty.

While unit emissions of particles and aerosol precursors from combustion processes are well quantified, non-exhaust emissions are more uncertain, and suspension of natural or road dust is not well quantified at all. Road dust resuspension is only considered in the roadside increment in our scheme, where it is included in the residual from calculated PM_{2.5} increment to the full PM₁₀ increment. However, this simple scheme does not take account of the many factors usually considered in detailed road dust resuspension models such as Nortrip (Denby et al., 2013). Detailed input data as required in these models are not readily available for hundreds of roadside monitoring stations in Europe. The estimation of fine and coarse roadside increment from the proportionality to the NO_x increment creates a strong dependency on the quality of observations, particularly on inter-comparability of PM and NO_x observations.

PM concentrations are subject to strong inter-annual variability (see Fig. 6) due to changeable meteorological conditions and dust episodes. Due to practical limitations in computing time, the urban increment calculation with 7 km × 7 km resolution could only be performed for one year, which was selected as the most recent year with AirBase observations and meteorological fields available at the starting time of this work. Judging from the historical trend shown in Fig. 6, 2009 does not seem to show unusually high or low concentrations in relation to other years on the European average; however, we do acknowledge that the reliance on one year introduces systematic station related uncertainty in modelled concentrations for the future.

Given the uncertainties and approximations, it is clear that this modelling scheme is not able to, nor is it supposed to, substitute detailed local scale modelling. A Europe-wide integrated model must make compromises, and there is definitely space for refinements in the methodology in the future. Results for individual stations need to be used with care, results are best analysed as an ensemble. Still, as a more detailed look at individual stations shows, the model is able to give a reasonable representation of different stations with different characteristics (Sect. 5.1). Hence, it offers the unique possibility of studying – with all uncertainties and caveats mentioned – the effects of Europe-wide air quality policy choices on ambient concentrations at the whole variety of monitoring stations available in Europe, and to estimate the remaining compliance gap left by EU wide legislation, which is supposed to be closed by additional measures on national level and local level.

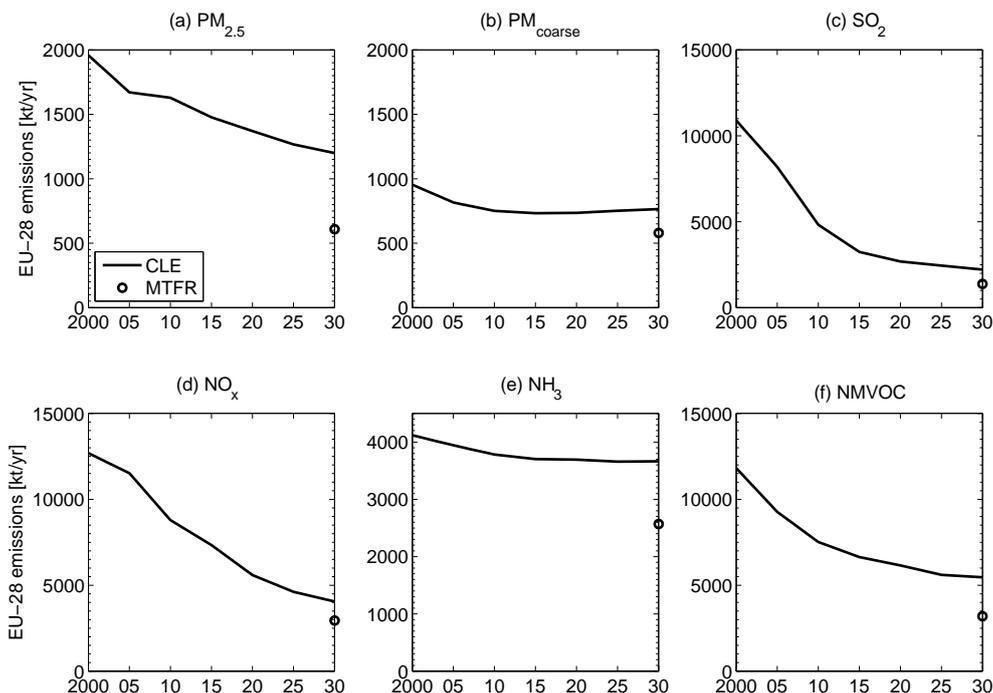


Figure 9. Bottom up calculated emissions of PM and its precursor gases in the EU-28 under current legislation (lines) and the maximum technically feasible reductions in 2030 (circles).

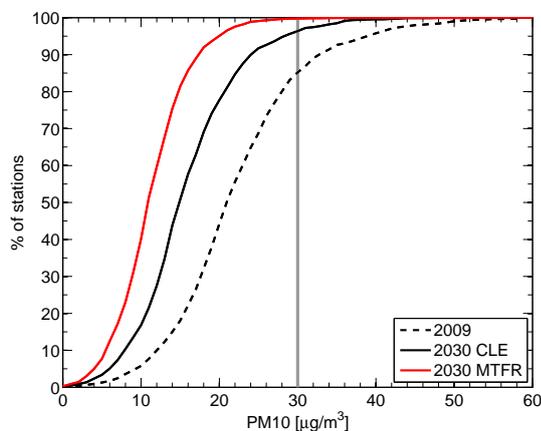


Figure 10. Cumulative distribution of PM₁₀ concentrations modelled at all stations covered in GAINS, for the base year 2009 and scenario year 2030, assuming either current legislation (CLE) or maximum technically feasible emission reductions (MTRF). The equivalent annual mean limit value of 30 µg m⁻³ is indicated as grey line. Natural contributions are not included.

5 Results and discussion

This section applies the modelling scheme introduced in this article to quantify source contributions to PM₁₀ concentrations for a set of critical stations (Sect. 5.1), and to provide an outlook on the evolution of Europe-wide PM₁₀ concentra-

tions and the possible attainment of limit values under future emissions (Sect. 5.2).

5.1 Source allocation of PM₁₀: examples of critical stations

Thanks to the structure of the model, the source composition of modelled PM₁₀ in terms of component and origin can be traced for every single station. This section attempts to give some examples for source attributions of PM₁₀ at urban monitoring stations in the base year.

Figure 7 shows the spatial allocation of origin for seven monitoring stations in the base year. The set is rather arbitrary but stations were selected as examples for critical stations with different characteristics. PM₁₀ concentrations are disaggregated into contributions from natural dust and sea salt, transboundary, national, urban, and street canyon increments, similar to the categories used e.g. by Lenschow et al. (2001); all of the anthropogenic contributions are further split into fine and coarse PM fractions. To arrive at the disaggregation shown here, regional background levels have been determined from the interpolation of nearby rural background stations, and unexplained residuals are allocated to missing emissions as described in Sect. 2.3. Before the re-allocation, residuals at these stations were between -20 % and 20 %.

Stations selected here are located in Paris (FR04058, A1 Saint Denis), Krakow (PL0038 A³), Turin (IT0469A,

³AirBase station name: MpKrakowWIOSPrad6115

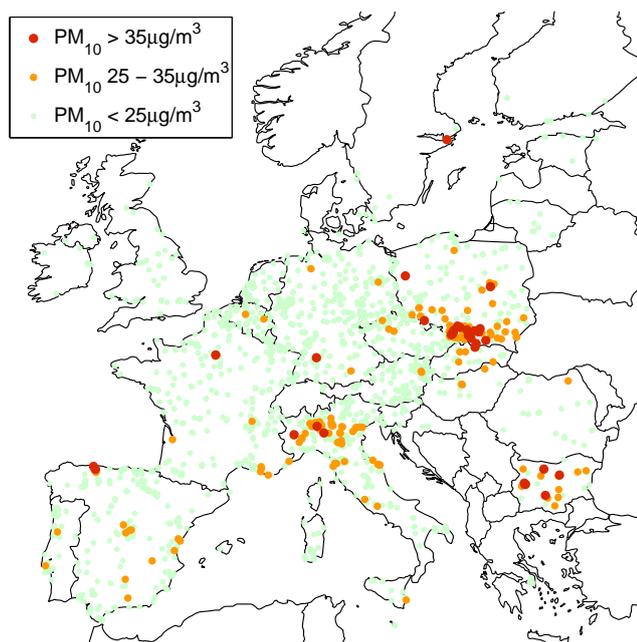


Figure 11. Modelled annual mean PM₁₀ concentrations at AirBase stations for the year 2030 under the CLE scenario.

Consolata), Stockholm (SE0003A, Hornsgatan), Essen (DENW134, Gladbecker Str.), London (GB0682A, Marylebone Road), and Vienna (AT9RINN, Rinnböckstraße). While all of these stations exceeded the $30\ \mu\text{g m}^{-3}$ equivalent limit value in 2009, source allocations show large differences in the reasons for the exceedances. Five of the six stations shown are traffic stations, with Krakow – the station with the second highest 2009 annual mean among them – being the only exception as an urban background station. With urban background concentrations at this level, the situation at curbside locations may be expected to be even worse. All spatial source categories shown have their part, although contributions of each fraction vary strongly between stations: while Turin is shielded by the Alps and consequently transboundary transport contributes only little to ambient PM, Vienna or Essen are significantly influenced by transboundary transport of pollution due to their geographical locations. Conversely, a high regional background related to Italian emissions is found in Turin, whereas in Stockholm the influence of Swedish emissions outside the city itself is almost negligible. The regional background, composed of natural, transboundary and national contributions, is around $20\ \mu\text{g m}^{-3}$ in most of the cities included here; lower levels are found in London and Stockholm. Such regional background levels leave only little room for urban and roadside increments if a limit of $30\ \mu\text{g m}^{-3}$ is to be matched, pointing to the multi-scale nature of the problem.

Focussing more on the local contributions, extreme differences are seen in both the urban and roadside increments, relating to local emission densities in the domestic and trans-

port sectors as well as to atmospheric mixing conditions in the boundary layer (for the urban increment) or the layout of the street canyon. Note the strong differences regarding the split of the roadside increment into fine and coarse PM fractions as estimated using the observed NO_x increment. While the fine fraction, caused mostly by exhaust emissions, slightly dominates at most stations, a dominating coarse component is found in regions with intensive use of traction sanding in winter or even studded tires such as in Stockholm. Both extreme examples, London Marylebone Road (large fine increment) and Hornsgatan (large coarse increment), offer PM_{2.5} observations in AirBase which confirm the split of the roadside increment; in Turin and Vienna the PM_{coarse} fraction of the roadside increment seems rather high and may be a bit over-estimated.

The highest roadside increment is seen in the Paris station, which is understandable as it is located at a suburban highway. Measurements at a station in Paris, comparable to the station chosen here, report for the year 2010 a fine fraction of the roadside increment of 62 % (AIRPARIF, 2011b), which is a bit higher than the share estimated in our model using the NO_x increment (54 % fine). This may be due to the different emission characteristics (fleet and speed) at a highway as compared to urban driving conditions which are assumed here; if national average driving conditions are assumed, the estimated fine share increases to 58 %.

A large roadside increment can be viewed as an opportunity – if the main cause of the problem is a local one, local action has a chance to alleviate the problem. If, on the other hand, only Europe-wide policy measures are adopted, which address only the fine, combustion generated particulates, cities with strong resuspension of road dust will face severe difficulties in reducing ambient concentrations.

Figure 8 shows the chemical composition of PM at the same set of monitoring stations as before. Chemical constituents are split up into natural, primary anthropogenic PM (PPM), secondary inorganic aerosol (SIA), and secondary organic aerosol (SOA), for both fine and coarse fractions. The primary coarse component includes non-exhaust emissions and resuspended dust, which is not distinguished explicitly in the model.

Comparing the chemical composition to observations is challenging for two reasons. Firstly, measured composition data are usually only available on a short term basis, often for episodes of high pollution; however, during such episodes the contributions can deviate significantly from the annual mean. Secondly, measured source categories are not easily translated into composition as modelled in GAINS. Hence, while a complete validation of the chemical composition is beyond the scope of this article, the purpose of this section is to point out a few characteristics.

The fine fraction constitutes about two-thirds (59–73 %) of total PM₁₀ at six out of the seven stations, with Stockholm being the only exception (only 27 %) for the reasons discussed above. As for the spatial origin of PM, large differ-

ences are also encountered in terms of chemical composition. Dust and sea salt contribute 1–5 $\mu\text{g m}^{-3}$ to PM₁₀, mostly in the coarse fraction. The largest contribution to PM₁₀ comes from primary particles (49–85 %); however, in the fine fraction, secondary aerosol concentrations are slightly higher than primary ones in Vienna and Essen.

Secondary inorganic aerosol concentrations are straightforward to be compared to observations. AIRPARIF (2011b) report SIA concentrations of 6.5 $\mu\text{g m}^{-3}$ at Paris roadside locations, which is matched well by GAINS (6.3 $\mu\text{g m}^{-3}$). For Vienna, Bauer et al. (2006) give annual average SIA concentrations of 11 $\mu\text{g m}^{-3}$, close to the values shown in Fig. 8 (10.5 $\mu\text{g m}^{-3}$); however, measurements were made in 2004. In Stockholm, SIA formation is considerably lower, with the 3.6 $\mu\text{g m}^{-3}$ modelled in the range of observations reported by Querol et al. (2004) (3–5 $\mu\text{g m}^{-3}$).

Among the stations included here, the highest SIA contribution in absolute terms is modelled in Krakow (12.7 $\mu\text{g m}^{-3}$) due to high SO₂ emissions and subsequent sulfate formation in this region. Overall, SIA contributes 10 % (Stockholm) to 34 % (Vienna) to PM₁₀. 80–95 % of the SIA is in the fine fraction of PM, with only minor contributions in the coarse fraction (essentially NaNO₃). Secondary organic aerosol formation is modelled but not of significant importance (0.3–2.1 $\mu\text{g m}^{-3}$ or 1–6 % of PM_{2.5}), with the highest values found in Turin.

Due to the simplifications of the model construction, the source attribution presented here can only give a rough estimate. It is meant to show the differences between individual stations and regions rather than provide exact results for which urban scale modelling based on local emission inventories is needed.

5.2 An outlook on the attainment of air quality standards

The modelling scheme described in this article has been applied in the ongoing revision of the EU air quality legislation to derive estimates of compliance with limit values under various emission scenarios. Here we show results for two specific scenarios, assuming either a political stagnation at currently approved emission control legislation levels (“CLE” is the current legislation scenario), or a very ambitious policy scenario applying the most efficient control technologies available (“MTFR” is the maximum technically feasible reductions scenario).

Figure 9 shows the trends of PM and precursor gas emissions under the scenarios used. The CLE scenario was used as the baseline case for the revision of the EU Thematic Strategy on Air Pollution (TSAP); it has been described in detail by Amann et al. (2013), with recent updates described by Amann et al. (2014).

Considerable decreases in PM_{2.5} and SO₂, NO_x and volatile organic compound emissions are expected under current legislation from ongoing implementation of exhaust

cleaning technologies. No further reductions are expected for PM_{coarse}, and hardly any for NH₃ emissions.

Analysis conducted for the TSAP revision has highlighted the potential for emission reductions beyond the baseline case. The MTFR scenario assumes that (within certain limitations of feasibility) all pollution sources are equipped with the best available emission control technology. Emissions under the MTFR scenario for 2030 are shown as circles in Fig. 9. Considerable reductions beyond the baseline are possible for all pollutants, however, this may come at relatively high costs. Realistic strategies are usually based on a partial closure of the gap between baseline and full application of the best available technologies. The strength of the GAINS model is then to find cost-optimal solutions for given health or air quality targets. However hypothetical for practical implementation, the MTFR scenario provides a quantification of what is possible in terms of emission reductions *without changing the levels of anthropogenic activities*, i.e. no behavioural changes and no switches to other fuel classes or renewable energy generation other than assumed in the baseline case which relies on the latest PRIMES-2013 scenario for energy consumption.

Figure 10 shows distributions of modelled PM₁₀ concentrations at all stations covered in the modelling scheme, for the base year as well as the scenario year 2030, comparing the modelled evolution under CLE and MTFR scenarios. Since EU legislation allows for natural contributions to be subtracted from measured concentrations, dust and sea salt fields as used in the EMEP model are subtracted here from total modelled concentrations⁴. While about 320 (17 %) of the stations exceed the equivalent limit value of 30 $\mu\text{g m}^{-3}$ in 2009 (dashed), increasing controls on emissions are expected to result in decreasing concentrations and consequently a higher fraction of attainment of the limit value across the EU already in the baseline case. However, after 2020 concentration decreases are slow, and about 80 (4.2 %) of the stations operative in 2009 are expected to remain above the equivalent limit value in 2030. A large amount of stations remains close to the equivalent limit value, so that definite statements about compliance are difficult.

Considering that the equivalent limit value is defined on a statistical base, with some stations exceeding the daily limit value even at annual mean concentrations below 30 $\mu\text{g m}^{-3}$ (Fig. 1), and also taking into account inter-annual meteorological variability, only stations below 25 $\mu\text{g m}^{-3}$ should be considered to be in safe compliance. This 5 $\mu\text{g m}^{-3}$ margin corresponds to the mean range of inter-annual Europe-wide PM₁₀ variations as seen in Fig. 6, and is also an uncertainty range for compliance with the daily mean limit value for a given annual mean concentration. More than 10 % of the sta-

⁴Technically, also contributions from traction sanding in winter may be neglected when determining compliance, which is particularly relevant for Nordic countries; however, as our model does not quantify this fraction explicitly, we do not subtract it here.

tions are not expected to meet this 25 µg m⁻³ limit in 2030 under CLE assumptions.

Full propagation of the maximum technically feasible emission reduction technologies would improve the compliance situation drastically, eliminating close to all stations above 30 µg m⁻³ (0.3%), and bringing 99% of the stations below 25 µg m⁻³. Several stations remain at annual mean concentrations close to the limit value, so that attainment of the limit value is not certain, particularly in years with unfavourable meteorological conditions. Additional local efforts may be warranted to ensure compliance in these cases.

Critical areas are identified easily in Fig. 11 showing a map of air quality monitoring stations colour coded by their modelled PM₁₀ concentrations under the CLE scenario in 2030. From the discussion above, only the “green” stations below 25 µg m⁻³ can be assumed to be in relatively safe compliance.

Difficulties are expected to remain in several European cities, Southern Poland and bordering areas in the Czech and Slovak Republics, Northern Italy, and Bulgaria. Different causes are responsible for the remaining difficulties: large cities are mainly under pressure from increasing traffic, with the unregulated non-exhaust emissions (and dust resuspension) eventually becoming dominant, while typically relatively clean fuels are used for household heating. If traffic volumes within large cities increase further, and if no additional measures on non-exhaust emissions are taken, several cities may move out of the compliance zone again.

Additional local measures targeting road traffic may be required to ensure safe attainment of the limit values, which may include the reduction of traffic volumes through local traffic management such as low emission zones or incentives for public transport use, the reduction of road dust abrasion through restrictions on studded tyre use in Scandinavian countries (Kupiainen and Pirjola, 2011), use of enhanced road surface material or advanced road cleaning/dust binding practices (Amato et al., 2010; Denier et al., 2013).

Eastern European countries, on the other hand, suffer from the widespread use of solid fuels such as low-grade coal or inefficient wood burning. Efficient emission cleaning technologies can improve the situation dramatically, as shown in Fig. 10; however, a hypothetical switch to cleaner fuels would provide for even better results.

6 Conclusions

This paper presents an introduction to the station based modelling methodology that has been introduced in the GAINS integrated assessment model to calculate concentrations of PM₁₀ and estimate compliance with limit values. Results are calculated for a total of about 1 870 monitoring stations reporting to AirBase. The modelling approach is based on explaining observed concentrations for the base year 2009 to the extent possible with a chain of simplified atmospheric

chemistry and transport calculations with models of different scales. Concentrations for other years are then calculated by substituting emissions from the GAINS bottom up emission calculation scheme.

Due to the complexity of the system involving different spatial scales, simplifications are necessary. The modelling scheme is not intended to replace detailed small scale dispersion modelling. The focus here is to provide an estimate of the effects of Europe-wide air quality policies on the attainment of limit values. Although results are calculated for each station individually, they are best evaluated on an ensemble base, as individual emission trends are not calculated for each station. On the contrary, GAINS quantifies for each station the effects of Europe-wide policy measures.

Different locations face different challenges for attaining safe PM levels. Both the geographical origin as well as the chemical composition vary considerably. While parts of the PM problem – particularly secondary aerosol formation – are related to transboundary transport in many EU Member States, calling for synchronised EU wide action, cities also suffer from the local increment generated mainly by household heating and road traffic.

Historical trends in observed concentrations are well reproduced by the model, a prerequisite for trustworthy conclusions on the future evolution. For the future, under the assumption of successful implementation of current legislation, reductions in ambient PM₁₀ concentrations are expected and consequently a higher attainment of the PM₁₀ limit value. However, current legislation is not expected to lead to Europe-wide attainment of the PM₁₀ limit value. Challenges are foreseen particularly in Eastern Europe, where widespread use of coal and inefficient wood burning in domestic heating hampers significant improvement, and in several major urban areas which suffer from increasing road traffic and stagnating household emissions. Considering that many of the remaining exceeding stations are located in densely populated areas, a significant proportion of the European population can be expected to remain exposed to PM concentrations violating EU air quality standards unless further political action is taken.

A range of technical emission control measures is readily available to decrease PM and precursor emissions beyond the baseline, as discussed by Amann et al. (2014). Exploiting the full range of emission controls available, concentrations could be decreased significantly further, and most cases of severe non-compliance persisting in 2030 could be eliminated. However, even in this scenario, safe attainment of the limit value is not achieved at all stations given uncertain meteorological conditions and possible single events. A solution could lie in the switch to cleaner fuels in domestic heating such as natural gas in Eastern European Member States.

Another challenge to safe attainment of limit values specific to urban areas is the possibly increasing burden of road and tire abrasion, and road dust resuspension. Although the linear relation between PM_{coarse} emissions and their con-

tributions to ambient concentrations that is used in this approach is pessimistic, it seems logical that more traffic generates more dust. A simple solution to this problem is yet to be found; targeted measures such as local traffic management (e.g. low emission zones), improved road surface material use, dust binding or enhanced road cleaning may be helpful to ensure that reductions in exhaust emissions are not compensated by increases in non-exhaust emissions and resuspended dust.

Acknowledgements. This work was partially supported by the EC4MACS (European Consortium for the Modelling of Air pollution and Climate Strategies) project with the contribution of the LIFE financial instrument of the European Community (contract no. LIFE06 ENV/PREP/A/000006), as well as the Service Contract on Monitoring and Assessment of Sectorial Implementation Actions (contract no. 07.0307/2011/599257/SER/C3) of DG-Environment of the European Commission. Monitoring data used in this study were obtained from AirBase (version 5).

Edited by: F. Dentener

References

- AIRPARIF: La Qualité de l'air en Île-de-France en 2010, Air-Parif Air quality monitoring network, Paris, France, http://www.airparif.asso.fr/_pdf/publications/bilan_2010.pdf, 2011a.
- AIRPARIF: Source apportionment of airborne particles in the Ile-de-France region, Paris, France, http://www.airparif.asso.fr/_pdf/publications/rapport-particu%les-anglais-120829.pdf, 2011b.
- Amann, M., Bertok, I., Borken-Kleefeld, J., Cofala, J., Heyes, C., Höglund-Isaksson, L., Klimont, Z., Nguyen, B., Posch, M., Rafaj, P., Sandler, R., Schöpp, W., Wagner, F., and Winiwarter, W.: Cost-effective control of air quality and greenhouse gases in Europe: Modeling and policy applications, *Environ. Modell. Softw.*, 26, 1489–1501, doi:10.1016/j.envsoft.2011.07.012, 2011.
- Amann, M., Borken-Kleefeld, J., Cofala, J., Hettelingh, J.-P., Heyes, C., Holland, M., Kieseewetter, G., Klimont, Z., Rafaj, P., Paasonen, P., Posch, M., Sander, R., Schoepp, W., Wagner, F., and Winiwarter, W.: Policy Scenarios for the Revision of the Thematic Strategy on Air Pollution, TSAP Report #10, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria, 2013.
- Amann, M., Borken-Kleefeld, J., Cofala, J., Hettelingh, J.-P., Heyes, C., Höglund, L., Holland, M., Kieseewetter, G., Klimont, Z., Rafaj, P., Posch, M., Sander, R., Schoepp, W., Wagner, F., and Winiwarter, W.: The final policy scenarios of the EU Clean Air Policy Package. TSAP Report #11, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria, 2014.
- Amato, F., Querol, X., Johansson, C., Nagl, C., and Alastuey, A.: A review on the effectiveness of street sweeping, washing and dust suppressants as urban PM control methods, *Sci. Tot. Environ.*, 408, 3070–3084, doi:10.1016/j.scitotenv.2010.04.025, 2010.
- Bauer, H., Marr, I., Kasper-Giebl, A., Limbeck, A., Caseiro, A., Handler, M., Jankowski, N., Klatzer, B., Kotianova, P., Poursmaeil, P., Schmidl, C., Sageder, M., and Puxbaum, H.: Endbericht für das Projekt "AQUELLA" Wien – Bestimmung von Immissionsbeiträgen in Feinstaubproben, Report UA/AQWien 2006r. Technical University of Vienna, Institute for Chemical Technologies and Analytics, Vienna, Austria, http://publik.tuwien.ac.at/files/PubDat_173988.pdf, 2006.
- Boulter, P. G.: A review of emission factors and models for road vehicle non-exhaust particulate matter, Published Project Report PPR065. TRL Limited, Wokingham, UK, http://uk-air.defra.gov.uk/assets/documents/reports/cat15/070%6061624_Report1_Review_of_Emission_Factors.PDF, 2005.
- Boulter, P. G., Thorpe, A. J., Harrison, R. M., and Allen, A. G.: Road vehicle non-exhaust particulate matter: Final report on emission modelling, Published Project Report PPR110, TRL Limited, Wokingham, UK, http://uk-air.defra.gov.uk/assets/documents/reports/cat15/070%6061624_Report2_Emission_modelling.PDF, 2006.
- Cuvelier, C., Thunis, P., Karam, D., Schaap, M., Hendriks, C., Kranenburg, R., Fagerli, H., Nyiri, A., Simpson, D., Wind, P., Schulz, M., Bessagnet, B., Colette, A., Terrenoire, E., Rouil, L., Stern, R., Graff, A., Baldasano, J., and Pay, M.: ScaleDep: Performance of European chemistry-transport models as function of horizontal spatial resolution, MSC-W Technical Report 1/2013, http://emep.int/publ/reports/2013/MSCW_technical_1_2013.pdf, 2013.
- Denby, B., Sundvor, I., Johansson, C., Pirjola, L., Ketzler, M., Norman, M., Kupiainen, K., Gustafsson, M., Blomqvist, G., and Omstedt, G.: A coupled road dust and surface moisture model to predict non-exhaust road traffic induced particle emissions (NORTRIP). Part 1: Road dust loading and suspension modelling, *Atmos. Environ.*, 77, 283–300, doi:10.1016/j.atmosenv.2013.04.069, 2013.
- Denier van der Gon, H. A. C., Gerlofs-Nijland, M., Gehrig, R., Gustafsson, M., Janssen, N., Harrison, R. M., Hulskotte, J., Johansson, C., Jozwicka, M., Keuken, M., Krijgsheld, K., Ntziachristos, L., Riediker, M., and Cassee, F. R.: The Policy Relevance of Wear Emissions from Road Transport, Now and in the Future – An International Workshop Report and Consensus Statement, *J. Air Waste Manage.*, 63, 136–149, doi:10.1080/10962247.2012.741055, 2013.
- EEA: Air quality in Europe – 2014 report, Report No. 5/2014. European Environment Agency, Copenhagen, DK, <http://www.eea.europa.eu/publications/air-quality-in-europe-%2014>, 2014.
- EU: Directive 2001/81/EC of the European Parliament and of the Council of 23 October 2001 on national emission ceilings for certain atmospheric pollutants (Offic J EU, 44, L 309, 27 November 2001, p. 22), 2001.
- EU: 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, Offic J EU, L 152, 11 June 2008, 1–44, 2008.
- Gustafsson, M., Blomqvist, G., Gudmundsson, A., Dahl, A., Jons-son, P., and Swietlicki, E.: Factors influencing PM₁₀ emissions from road pavement wear, *Atmos. Environ.*, 43, 4699–4702, doi:10.1016/j.atmosenv.2008.04.028, 2009.
- Harrison, R., Jones, A., Gietl, J., Yin, J., and Green, D.: Estimation of the contributions of brake dust, tire wear, and resuspension to nonexhaust traffic particles derived from atmospheric measurements, *Environ. Sci. Technol.*, 46, 6523–6529, 2012.

- Harrison, R. M., Yin, J., Mark, D., Stedman, J., Appleby, R. S., Booker, J., and Moorcroft, S.: Studies of the coarse particle (2.5–10 µm) component in UK urban atmospheres, *Atmos. Environ.*, 35, 3667–3679, doi:10.1016/S1352-2310(00)00526-4, 2001.
- Hauck, H., Berner, A., Gomiscek, B., Stopper, S., Puxbaum, H., Kundi, M., and Preining, O.: On the equivalence of gravimetric PM data with TEOM and beta-attenuation measurements, *J. Aerosol Sci.*, 35, 1135–1149, 2004.
- Kassomenos, P., Vardoulakis, S., Chaloulakou, A., Paschalidou, A., Grivas, G., Borge, R. and Lumbreras, J.: Study of PM₁₀ and PM_{2.5} levels in three European cities: Analysis of intra and inter urban variations, *Atmospheric Environment*, 48, 153–163, doi:10.1016/j.atmosenv.2014.01.004, 2014.
- Kiesewetter, G., Borken-Kleefeld, J., Schöpp, W., Heyes, C., Thunis, P., Bessagnet, B., Terrenoire, E., Gsella, A., and Amann, M.: Modelling NO₂ concentrations at the street level in the GAINS integrated assessment model: Projections under current legislation, *Atmos. Chem. Phys.*, 14, 813–829, doi:10.5194/acp-14-813-2014, 2014.
- Klimont, Z., Cofala, J., Bertok, I., Amann, M., Heyes, C., and Gyarfas, F.: Modelling Particulate Emissions in Europe. A Framework to Estimate Reduction Potential and Control Costs, IIASA Interim Report IR-02-076, International Institute for Applied Systems Analysis, Laxenburg, Austria, 2002.
- Kupiainen, K., Tervahattu, H., Räisänen, M., Mäkelä, T., Aurela, M., and Hillamo, R.: Size and composition of airborne particles from pavement wear, tires, and traction sanding, *Environ. Sci. Technol.*, 39, 699–706, doi:10.1021/es035419e, 2005.
- Kupiainen, K. J. and Pirjola, L.: Vehicle non-exhaust emissions from the tyre-road interface – effect of stud properties, traction sanding and resuspension, *Atmospheric Environment*, 45, 4141–4146, doi:10.1016/j.atmosenv.2011.05.027, 2011.
- Lenschow, P., Abraham, H.-J., Kutzner, K., Lutz, M., Preuß, J.-D., and Reichenbacher, W.: Some ideas about the sources of PM₁₀, *Atmos. Environ.*, 35, Supplement 1, S23–S33, doi:10.1016/S1352-2310(01)00122-4, 2001.
- Menut, L., Bessagnet, B., Khvorostyanov, D., Beekmann, M., Blond, N., Colette, A., Coll, I., Curci, G., Foret, F., Hodzic, A., Mailler, S., Meleux, F., Monge, J., Pison, I., Siour, G., Turquety, S., Valari, M., Vautard, R., and Vivanco, M.: CHIMERE 2013: a model for regional atmospheric composition modelling, *Geosci. Model Develop.*, 6, 981–1028, 2013.
- Querol, X., Alastuey, A., Ruiz, C., Artiñano, B., Hansson, H., Harrison, R., Buringh, E., Ten Brink, H., Lutz, M., Bruckmann, P., Straehl, P., and Schneider, J.: Speciation and origin of PM₁₀ and PM_{2.5} in selected European cities, *Atmos. Environ.*, 38, 6547–6555, doi:10.1016/j.atmosenv.2004.08.037, 2004.
- Rouil, L. and Bessagnet, B.: How to start with PM modelling for air quality assessment and planning relevant to the Air Quality Directive, ETC/ACM Technical Paper 2013/11, European Topic Centre on Air Pollution and Climate Change Mitigation, Bilthoven, Netherlands, 2013.
- Simpson, D., Benedictow, A., Berge, H., Bergström, R., Emberson, L. D., Fagerli, H., Flechard, C. R., Hayman, G. D., Gauss, M., Jonson, J. E., Jenkin, M. E., Nyíri, A., Richter, C., Semeena, V. S., Tsyro, S., Tuovinen, J.-P., Valdebenito, Á., and Wind, P.: The EMEP MSC-W chemical transport model – technical description, *Atmos. Chem. Phys.*, 12, 7825–7865, doi:10.5194/acp-12-7825-2012, 2012.
- Stedman, J. R., Kent, A. J., Grice, S., Bush, T. J., and Derwent, R. G.: A consistent method for modelling PM₁₀ and PM_{2.5} concentrations across the United Kingdom in 2004 for air quality assessment, *Atmos. Environ.*, 41, 161–172, doi:10.1016/j.atmosenv.2006.07.048, 2007.
- Thorpe, A. and Harrison, R. M.: Sources and properties of non-exhaust particulate matter from road traffic: A review, *Sci. Total Environ.*, 400, 270–282, doi:10.1016/j.scitotenv.2008.06.007, 2008.
- Thunis, P., Pederzoli, A., and Pernigotti, D.: Performance criteria to evaluate air quality modeling applications, *Atmos. Environ.*, 59, 476–482, doi:10.1016/j.atmosenv.2012.05.043, 2012.
- UNECE: Protocol to the 1979 Convention on Long-Range Transboundary Air Pollution to abate acidification, eutrophication and ground-level ozone. United Nations Economic Commission for Europe, Geneva, Switzerland, 1999.
- WHO: Health Aspects of Air Pollution with Particulate Matter, Ozone and Nitrogen Dioxide, Report on a WHO Working Group, World Health Organization, Bonn, Germany, 2003.
- WHO: Review of evidence on health aspects of air pollution – REVIHAAP Project, Technical Report, World Health Organization Regional Office for Europe, Copenhagen, Denmark, 2013.