



Air quality and related health impact in the UNECE region: source attribution and scenario analysis

Claudio A. Belis and Rita Van Dingenen

European Commission, Joint Research Centre, Via Fermi 2749, 21027 Ispra, Italy

Correspondence: Claudio A. Belis (claudio.belis@ec.europa.eu)

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Abstract. The TM5-FAst Scenario Screening Tool (TM5-FASST) was used to study the influence of abatement policies within and outside the United Nations Economic Commission for Europe (UNECE) region on the exposure to O₃ and PM_{2.5} and associated mortality in the UNECE countries. To that end, the impacts of pollutants derived from different geographic areas and activity sectors were evaluated using ECLIPSE V6b scenarios of air pollutant and greenhouse gas (GHG) emission reduction. The mortalities were attributed to O₃ and PM_{2.5} following the Global Burden of Disease (GBD) approach and allocated to geographic areas (UNECE and non-UNECE) and activity sectors, including natural sources. In addition, a combination of runs designed for the purpose led to allocating exposure to O₃ and related mortality to two families of precursors: NO_x–VOC and CH₄. In this study, the baseline scenario (current legislation scenario, CLE), which assumes that all air quality and greenhouse gas abatement measures adopted by 2018 are fully implemented, is compared with more ambitious scenarios (maximum feasible reduction, MFR). The findings from this comparison indicate that O₃ exposure within the UNECE area is more sensitive to measures outside the UNECE region than PM_{2.5} exposure, even though the latter leads to higher mortality than the former. In the CLE, the mortality associated with O₃ exposure in the UNECE region grows steadily from 2020 to 2050. The upward trend is mainly associated with the growing impact of CH₄ emissions from areas outside UNECE. Also, the mortality related to NO_x–VOC emissions outside UNECE increases in the same period. By comparison, a measurable decrease (13 %) is observed in the mortality attributable to NO_x–VOC emissions within UNECE. In the same time window, the mortality associated with PM_{2.5} exposure in the UNECE region decreases between 2020 and 2040 and then rises until 2050. The PM_{2.5}-related mortality in UNECE is mainly due to anthropogenic emissions within this region followed by natural sources (sea salt and dust) mainly located outside the UNECE region. Between 2020 and 2050, the impact of some UNECE anthropogenic sources on PM_{2.5}-related mortality decreases progressively, in particular road transport, energy production and domestic combustion, while others, namely agriculture and industry, show an upward trend. Finally, the analysis of MFR scenarios confirms that abatement measures in line with UN Sustainable Development Goals (SDGs) and the Paris Agreement can lead to significant co-benefits between air quality and climate policies.

1 Introduction

In 2019, 6.67 million deaths globally (equivalent to 12 % of the total deaths) were attributed to air pollution exposure, mainly due to fine particles and ozone (HEI, 2020). Air pollution is the main environmental risk of premature death worldwide. However, the gap between low- and medium-income countries (LMIC) and high-income countries (HIC)

has widened since the beginning of this century due to the increasing trend of PM_{2.5}-related mortality in the former (Burnett and Cohen, 2020).

The Convention on Long-Range Transport of Air Pollution (also known as “the Air Convention”) of the United Nations Economic Commission for Europe (UNECE) was adopted in

1979 and at present has 56 member states¹, including the EU since 1982. It has eight protocols, four of which are active. The Gothenburg Protocol to abate acidification, eutrophication and ground-level ozone is under review and an evaluation is in progress to assess the adequacy of its obligations and provisions. One of the aspects under evaluation is the future trend for improvements in air quality, human health and ecosystem impacts linked to methane (CH₄) emissions. Ground-level ozone (O₃) concentrations in most of the UNECE region countries are also influenced by other factors in addition to the regional ozone precursors: e.g. climatic parameters, hemispheric transport and global CH₄ emissions (Butler et al., 2020). Global background levels of O₃, PM_{2.5} and their precursors, including CH₄ emissions, contribute significantly to air pollution within the UNECE region, with impacts on public health, ecosystems and biodiversity (Jonson et al., 2018; Lefohn et al., 2018). Projected trends in anthropogenic CH₄ emissions span a very wide range, depending on assumptions made about economic development and the use of emission control technology (Revell et al., 2015; Turnock et al., 2018).

The Air Convention protocols have contributed to reducing air pollution in UNECE countries. However, it is becoming more and more relevant to evaluate which pollutant levels are most affected/controlled by long-range transport of emissions outside the UNECE area and to which extent new air quality guidelines can be achieved through emission reductions within UNECE only. This study aims to investigate the extent to which the abatement policies within the UNECE region and those in the rest of the world (ROW) influence the exposure to O₃, PM_{2.5} and their associated mortality in the UNECE countries. To that end, the impacts of pollutants derived from different geographic areas and activity sources that contribute to mortality related to air quality in the UNECE region are analysed under different abatement scenarios of air pollutants and greenhouse gas (GHG) emissions. The emphasis is on quantifying the achievable benefits by analysing the gap between scenarios with different levels of ambition and the baseline. In particular, one of the maximum feasible reduction (MFR) scenarios (MFR BASE) is mainly driven by technological development connected to air pollutant emissions combined with a basic set of climate-oriented policies (national determined contributions), while the other scenario (MFR sustainable development scenario, MFR-SDS) is an archetype of the potentially achievable re-

ductions by implementing the UN Sustainable Development Goals (SDGs) related to energy combined with ambitious climate-oriented policies.

2 Methods

2.1 Exposure and health impact assessment

The TM5-FAst Scenario Screening Tool (TM5-FASST) is a reduced-form air quality model based on linearized emission-concentration response sensitivities (also called source-receptor coefficients). The emission-concentration responses to regional emission changes were pre-computed at a 1° × 1° grid resolution with the full chemical transport model (CTM) TM5 (Krol et al., 2005) for 56 continental source regions, as well as for international shipping and aviation, for an emission reduction of 20 % in each of the relevant pollutant precursors (SO₂, NO_x, NH₃, BC, OC, NMVOC) and for each individual source region. The resulting deviation relative to the unperturbed case in ground-level pollutant concentrations is assumed to scale linearly with the emission deviation relative to the unperturbed case. More details are given in the Supplement.

The TM5-FASST model bypasses CPU-expensive explicit chemical and physical process computations, at the cost of accuracy, as documented by Van Dingenen et al. (2018). It is worth mentioning that the model addresses impacts of anthropogenic emissions under constant meteorological conditions (year 2001), and therefore does not consider feedbacks of climate on photolysis rates, precursor residence times and deposition rates etc. This also implies that natural emissions of volatile organic components (including natural CH₄), NO_x, as well as natural PM_{2.5}, are treated as fixed, constant contributions. Still, without claiming to be quantitatively equivalent to a full CTM, the model captures major features and implications of emission trends and has proven to be a useful screening tool in science-policy analysis (Van Dingenen et al., 2018).

A great advantage of a source-receptor model is that it keeps track of the contribution of each of the 56 + 2 source regions, as well as each individual precursor, to each receptor grid cell of the global domain, under the first-order assumption that all contributions can be added up linearly. This makes the model particularly useful for source attribution studies, which can be applied with a large degree of flexibility in the definition of the receptor regions, the latter being a customizable aggregation of grid cells. In this study, we consider as receptor region the UNECE domain, and we explore contributions of pollutant emissions outside and inside the UNECE region. Further detail in the attribution studies is obtained by breaking down the emissions by anthropogenic sector.

Health-relevant exposure metrics considered in the present study are the population-weighted PM_{2.5} concentrations (as the sum of sulfate, nitrate, ammonium and primary

¹Albania, Armenia, Austria, Azerbaijan, Belarus, Belgium, Bosnia and Herzegovina, Bulgaria, Canada, Croatia, Cyprus, Czech Republic, Denmark, Estonia, European Union, Finland, France, Georgia, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Kazakhstan, Kyrgyzstan, Latvia, Liechtenstein, Lithuania, Luxembourg, Malta, Monaco, Montenegro, Netherlands, North Macedonia, Norway, Poland, Portugal, Republic of Moldova, Romania, Russian Federation, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Tajikistan, Türkiye, Turkmenistan, Ukraine, United Kingdom, United States of America and Uzbekistan.

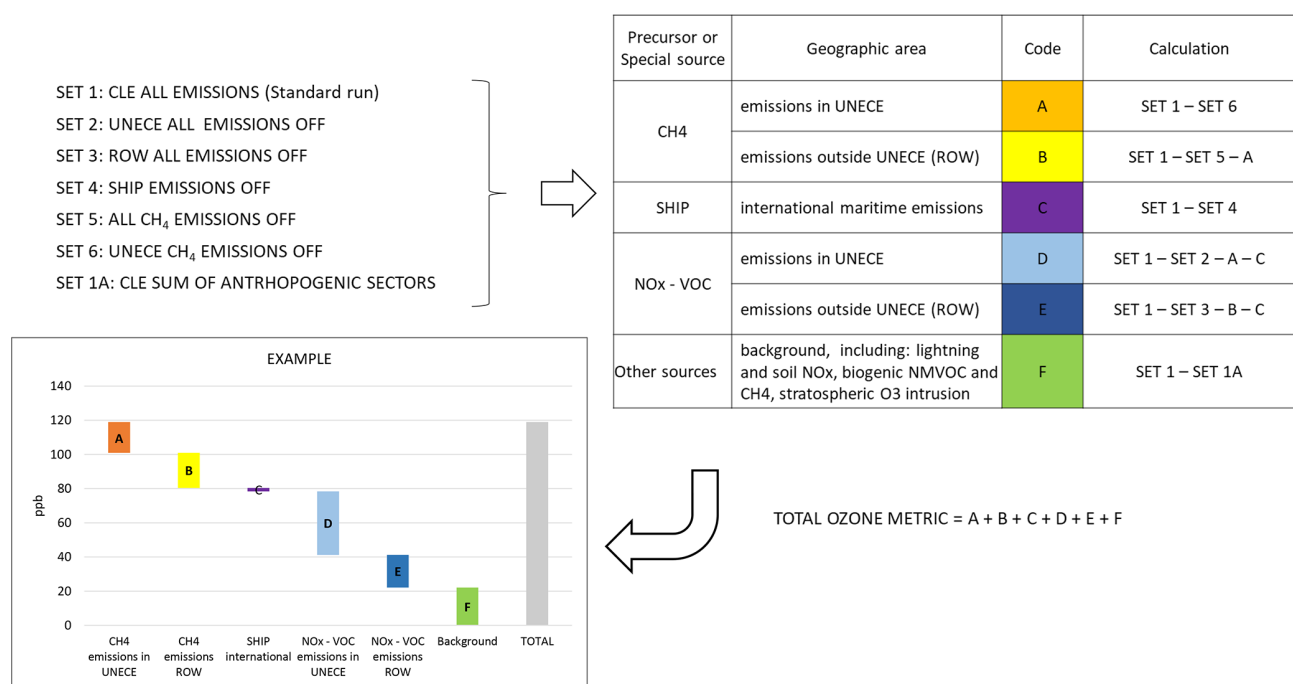


Figure 1. Approach adopted to split O₃ concentrations by emission area (UNECE and non-UNECE (ROW)) and by precursor (NO_x–VOC and CH₄).

PM_{2.5}) and the seasonal daily maximum 8 h ozone average (SDMA8h). We apply a sub-grid correction to account for the spatial correlation between population density and primary PM_{2.5} associated with transport and household emissions, leading to a higher estimated exposure than the value based on a uniform PM_{2.5} distribution across the 1° × 1° grid. This is relevant where strong population gradients occur within a single grid (Van Dingenen et al., 2018). Details of the applied parameterization are given in the Supplement.

The mortality associated with exposure to outdoor pollutants is estimated according to the Global Burden of Disease (GBD) approach (Stanaway et al., 2018). The methodology to estimate the health impacts of air quality is given in the Supplement. A complete description and validation of the TM5-FASST model is provided in Van Dingenen et al. (2018), Sampedro et al. (2022) and Belis et al. (2022).

2.2 Sources

The contributions (or impacts) from anthropogenic sectors and natural emissions to PM_{2.5} and O₃ exposure metrics in the UNECE region are estimated by the so-called brute-force or emission reduction impact approach (Belis et al., 2020, 2021). The impact of the following anthropogenic activity sectors (11) was quantified: agriculture (AGR), agricultural waste burning (AWB), domestic and commercial combustion (DOM), energy production (ENE), industry (IND), use of solvents (SLV), road transport (TRA), gas flaring (FLR), waste management (WST), open biomass burning

(BMB) and maritime (SHP). Historical fire emissions were added from van Marle et al. (2017) and projections from the harmonized CMIP6 SSP2 scenario (Feng et al., 2020), including large-scale biomass burning and savannah burning and excluding AWB emissions to avoid double counting with the ECLIPSE V6b emissions. The resulting anthropogenic PM_{2.5} concentration fields are overlaid with fixed natural PM_{2.5} sources – dust (DUST) and sea salt (SS) – taken as the average of the CAMS reanalysis for the years 2000 to 2008 (<https://www.ecmwf.int/en/forecasts/dataset/cams-global-reanalysis>, last access: 18 July 2023). For O₃, the above-mentioned sectoral attribution was complemented with runs separating the impact of NO_x–NMVOC (hereon NO_x–VOC) and CH₄ precursor emissions from (1) UNECE (continental, anthropogenic), (2) ROW (rest of the world: non-UNECE continental, anthropogenic), (3) international shipping (hereon maritime) and (4) other sources, according to the scheme described in Fig. 1.

The standard simulations (set 1) include the emissions in each of the three ECLIPSE V6b scenarios as described in Sect. 2.3 (CLE, MFR BASE, MFR-SDS). In addition, a series of perturbations (sets 2 to 6) were computed in which the emissions of specific O₃ precursors (either NO_x–VOC or CH₄) were reduced worldwide or in specific areas (either UNECE or rest of the world) for each of the above-mentioned scenarios. A total of 18 simulations were computed: 1 for each of the 3 scenarios in each of the 6 sets. Subsequently, sets 1 to 6 were conveniently subtracted as described in Fig. 1 (right) to split the contributions/impacts

of UNECE countries from those of the rest of the world and allocate O₃ to its two families of precursors: NO_x–VOC or CH₄. International maritime emissions are allocated into a stand-alone category as they are not attributed to any geographic area (UNECE nor ROW). The category “other sources” includes emissions not allocated to any specific area nor precursor (e.g. lightning and soil NO_x, biogenic NMVOC and CH₄, stratospheric O₃ intrusion). In the analysis of the results, the apportionment by region and precursor described here was combined with the information about anthropogenic sources described at the beginning of this section.

In Appendix A, the PM_{2.5} and O₃ source apportionment presented in this study is compared with similar studies in the literature.

The obtained shares for the PM_{2.5} and O₃ exposure metrics are converted to total mortalities according to

$$\text{MORTALITY}_{\text{source } x} = \text{MORTALITY}_{\text{total}} \times \frac{\text{EXPOSURE METRIC}_{\text{source } x}}{\text{EXPOSURE METRIC}_{\text{total}}}, \quad (1)$$

where EXPOSURE METRIC_{total} is the sum of all individual sources (*x*) shares (Belis and Van Dingenen, 2023).

2.3 Scenarios

This study evaluates a set of scenarios (Appendix A, Table A1) derived from the ECLIPSE dataset version 6b (Amann et al., 2011; Klimont et al., 2017) developed using the GAINS model (IIASA, 2022). To assess different levels of ambition in the abatement policies from 2020 onwards, the CLE is compared with two maximum feasible reduction (MFR) scenarios: MFR BASE and MFR-SDS (Appendix A, Table A1). For every macro-sector (e.g. energy, transport, industry), each scenario combines a set of cross-cutting measures with others specific for each region of the world. The CLE and MFR BASE scenarios are based on the International Energy Agency’s (IEA) New Policy Scenario (NPS; IEA, 2018) which includes measures that had been announced by 2018 and makes no assumptions about further evolution of these positions nor aims to achieving any particular outcome. The NPS includes the European Union’s 2030 renewable energy and energy efficiency targets, the Chinese 3-year action plan for cleaner air, the planned revision of the Corporate Average Fuel Economy standards in the United States, as well as the announced US Affordable Clean Energy rule. Moreover, it considers Japan’s revised basic energy plan and Korea’s 8th National Electricity Plan. The climate policy for both CLE and MFR BASE is the same and is specific for every country as it is based on the countries’ national determined contributions (NDCs) under the Paris Agreement (<https://unfccc.int/process-and-meetings/the-paris-agreement/nationally-determined-contributions-ndcs>, last access: 18

July 2023). Examples of cross-cutting measures in the NPS are the fuel sulfur standards of 10–15 ppm in the road transport sector, a global cap of 0.5 % on sulfur content of fuel in 2020 in the international shipping sector, and the improvement of fuel efficiency by 2 % yr^{−1} until 2020 in the international aviation sector. The emission reduction in the MFR BASE scenario compared to the CLE is based on the introduction of best available technology (BAT) with no-cost limitations (Table A1).

Unlike the previous two, the MFR-SDS scenario is based on the IEA’s Sustainable Development Scenario (SDS; IEA, 2018) which includes the main energy-related components of the Sustainable Development Goals, agreed to by 193 countries in 2015 to keep the increase of global average temperature below 2 °C, achieving universal access to modern energy by 2030 and dramatically reducing the premature deaths due to energy-related air pollution. Examples of cross-cutting assumptions in the SDS are the staggered introduction of CO₂ prices, fossil fuel subsidies phased out by 2025 in net-importing countries and by 2035 in net-exporting countries, and the maximum sulfur content of oil products capped at 1 % for heavy fuel oil, 0.1 % for gas oil and 10 ppm for gasoline and diesel. A full description of the scenarios goes beyond the purposes of the present work. More details are available elsewhere (<https://iiasa.ac.at/models-tools-data/global-emission-fields-of-air-pollutants-and-ghgs>, last access: 18 July 2023; IEA, 2018; Belis et al., 2022).

In this study, the shared socio-economic pathway (SSP) gridded population projections from Jones and O’Neill (2016) were used. The SSP2 projections were associated with CLE and MFR BASE while SSP1 were used with the MFR-SDS scenario.

3 Results

3.1 Emissions

The UNECE and ROW emission trends between 2020 and 2050 of O₃ and PM_{2.5} precursors in all the studied scenarios are shown in Fig. 2. In the CLE scenario, UNECE NO_x, NMVOC and PM_{2.5} emissions decrease by 33 %, 13 % and 13 %, respectively, between 2020 and 2050, while in ROW, NH₃ and CH₄ increase by 27 % and 34 %, respectively.

In both MFR scenarios, UNECE emissions show a downward trend over the whole time window with the exception of NH₃, which remains stable after an initial decrease. Moreover, in these scenarios, NH₃ is the only precursor with a distinguishable upward emission trend between 2025 and 2050 in ROW while all the others show a downward trend. In MFR BASE, UNECE emissions in 2050 are between 69 % (PM_{2.5}) and 35 % (NH₃) lower than the CLE while ROW emissions are between 80 % (PM_{2.5}) and 37 % (NH₃) lower than the CLE. Despite MFR-SDS emissions following similar trends,

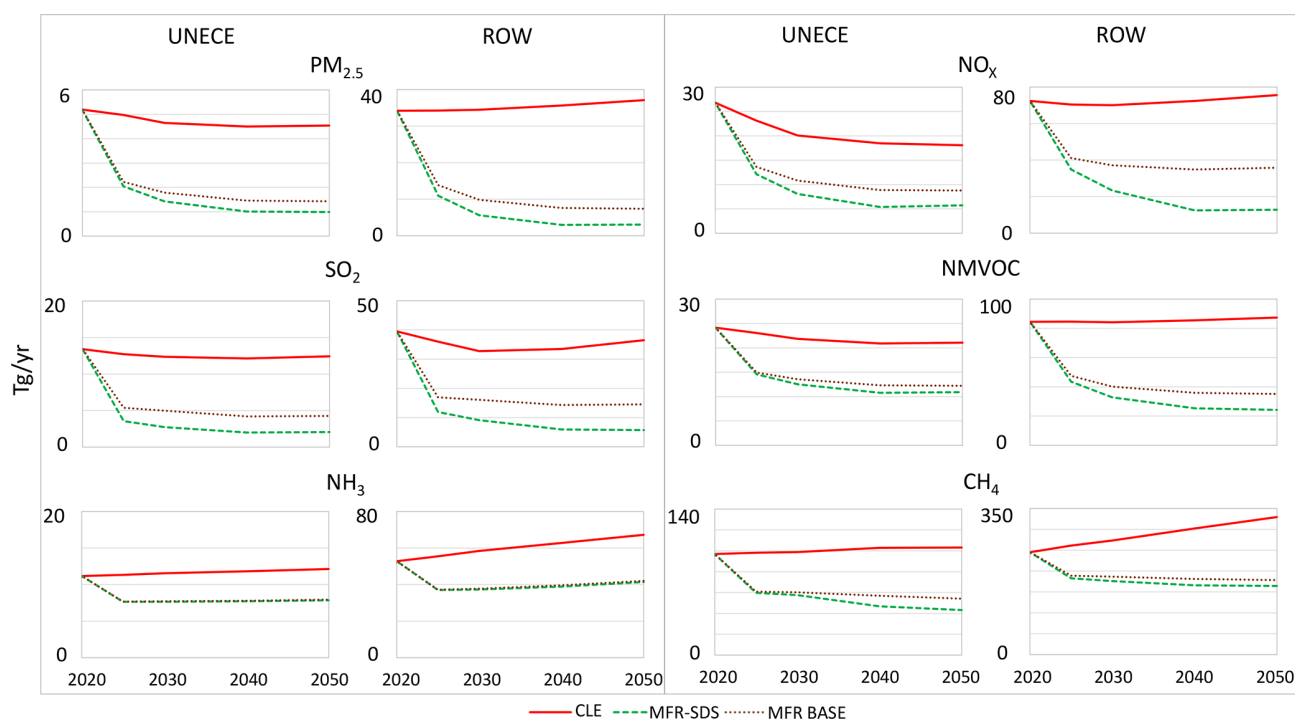


Figure 2. UNECE (left) and ROW (right) emission trends of the main O_3 and $PM_{2.5}$ precursors in the studied ECLIPSE V6b scenarios.

the reductions with respect to the CLE are higher, with the exception of NH_3 which is the same in both MFR scenarios.

3.2 Influence of ROW on UNECE

To assess the impact of air pollutant and GHG abatement measures outside the UNECE region (rest of the world; ROW) on UNECE emission abatement policies, a regional source attribution exercise is discussed in this section. The exposure to $PM_{2.5}$ (anthropogenic) and O_3 in UNECE countries between 2020 and 2050 in the global baseline scenario (CLE) is compared with the MFR BASE scenario and with a scenario in which the emission reductions foreseen in the MFR BASE are applied only in the UNECE region while CLE emissions are kept in ROW (MFR UNECE scenario) (Fig. 3).

The O_3 exposure in CLE (red line) and MFR UNECE (green line) shows an upward trend from 2025 onwards. The abatement benefit, i.e. the difference between the O_3 exposure in CLE and MFR UNECE, over the considered time window is relatively small (5 % to 6 %), suggesting that the application of emission reductions in UNECE countries only leads to limited additional abatement in the O_3 exposure in UNECE countries relative to the baseline (CLE). By comparison, the O_3 exposure in MFR BASE (yellow line) follows a downward trend and the abatement benefit (delta CLE–MFR BASE) is twice as much as MFR UNECE (10 % to 16 %), indicating that the implementation of MFR worldwide would

not only lead to higher abatement of exposure in UNECE but also reverse the trend from increasing to decreasing.

Unlike O_3 , $PM_{2.5}$ exposure shows a decreasing trend for the three scenarios. The abatement benefit (CLE–MFR UNECE) over the studied period is already high (–38 % to –41 %) and applying the MFR BASE scenario globally leads to a relatively small marginal benefit (≤ 10 % of CLE). In synthesis, for $PM_{2.5}$ abatement, UNECE is only slightly affected by ROW measures, while O_3 levels are strongly modulated by measures taken outside the UNECE region. This is obviously related to the longer (compared to $PM_{2.5}$) atmospheric lifetime of O_3 , formed from its short-lived precursors, NO_x and NMVOC, and its long-lived precursor CH_4 which contributes to the global background O_3 . The UNECE countries where the differences in O_3 and $PM_{2.5}$ exposure between MFR UNECE and MFR BASE are the highest (in the range 6 to 10 ppb and 1.5 to 2.4 $\mu g m^{-3}$, respectively) are located at the boundary of the UNECE region and therefore more exposed to long-range pollution from the ROW (Fig. S2 in the Supplement). Some of these countries are in the Caucasus and central Asia (Armenia, Azerbaijan, Tajikistan, Kyrgyzstan and Turkmenistan) downwind, highly polluted regions (e.g. southern Asia, Far East). The highest differences between these scenarios for both pollutants are observed in Israel which is a small country surrounded by an area of non-UNECE countries with high emissions. Some countries in the Atlantic coastal area (Portugal, Spain and Ireland) present high differences in the O_3 exposure between MFR UNECE and MFR BASE, likely due to the influence

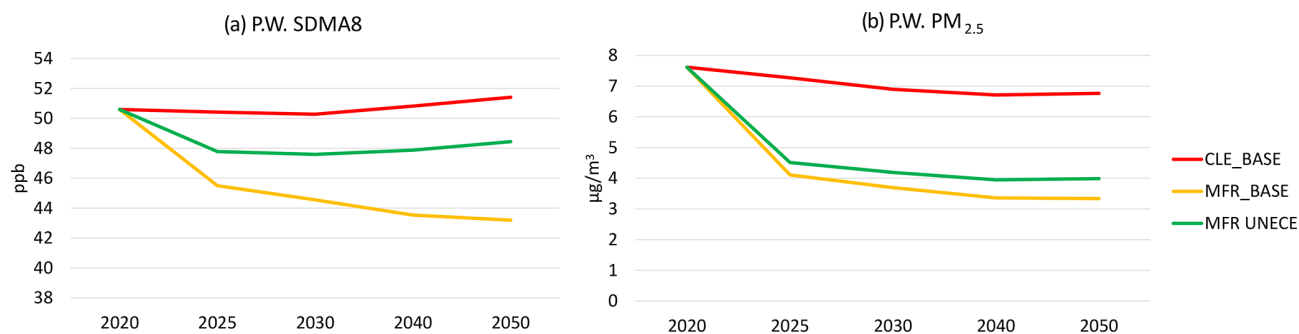


Figure 3. O₃ seasonal mean of 8 h (population-weighted SDMA8h, **a**) and anthropogenic population-weighted PM_{2.5} (**b**) annual averages in the UNECE region, average of countries, under different scenarios: CLE (current legislation), MFR BASE applied in UNECE countries only (MFR UNECE), MFR BASE in all countries (MFR BASE).

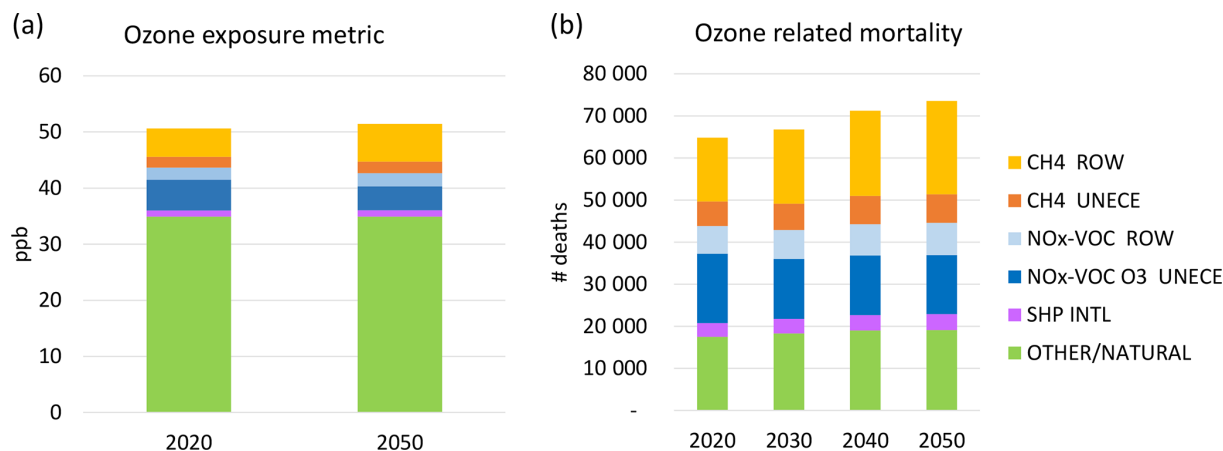


Figure 4. Allocation of the population-weighted O₃ (SDMA8h) exposure in UNECE to geographic source areas (UNECE, ROW), precursors and other/natural sources. Units: **(a)** parts per billion (ppb), **(b)** mortality (UNECE total) associated with O₃ exposure in UNECE split by natural background (only the fraction above the exposure threshold) and anthropogenic emissions.

of air masses circulating over the sea and mostly affected by emissions in ROW. A similar situation is observed in Malta which is mostly affected by the high background levels in the Mediterranean Sea.

The attribution of O₃ and PM_{2.5} levels to precursor emissions inside and outside the UNECE region is further investigated in the following sections.

3.3 Source allocation of ozone exposure and premature mortality in UNECE in the baseline scenario (CLE)

In this section, the O₃ exposure and related mortality within UNECE is broken down by (a) precursor, (b) sector and (c) source region (UNECE versus ROW) considering only the attribution runs of the CLE scenario. The O₃ background (other/natural), including biogenic and other unspecified sources (Fig. 4a), is estimated by subtracting the sum of all anthropogenic sectors from total O₃ (see Sect. 2.2) and is the main single contributor to the O₃ exposure. The impact of this “source” is approximately 35 ppb and remains relatively constant throughout the analysed time window (2020–2050).

Despite its dominance, this component is not the main focus of the analysis since it is, by design, affected only a little by anthropogenic emissions in the short term. In the 2020–2050 time window, the anthropogenic fraction of the O₃ exposure is worth 16–19 ppb.

In terms of precursors, there is a remarkable shift in the relative role of short-lived components (NO_x, NMVOC) versus CH₄ between 2020 and 2050 in CLE. The initial dominant role of NO_x and NMVOC in anthropogenic ozone formation is replaced by CH₄ towards 2050. This is due to the combined decrease of UNECE NO_x and NMVOC emissions (while ROW emissions remain relatively constant) and the increase of ROW CH₄ emissions (while UNECE emissions remain relatively constant). The overall O₃ exposure metric is stable along the observed time window because the decreasing impact of NO_x–VOC emissions from UNECE over time is largely compensated by the increasing impact of CH₄ emitted in ROW.

The overall share of O₃ exposure allocated to anthropogenic NO_x–VOC emissions is mainly associated with

transport, industry and maritime sources while the CH₄ emissions affecting this pollutant are mainly emitted from agriculture, gas flaring and waste management. Energy production, another important anthropogenic source, presents similar shares of both precursor families (Fig. S3).

In Fig. 4b the premature mortality associated with O₃ exposure in the UNECE region estimated in the CLE is shown. The number of premature deaths grows steadily from 65 000 in 2020 to 74 000 in 2050. This upward trend in mortality is mainly associated with an increased impact of anthropogenic CH₄ emissions from ROW (+46 %, +7000 deaths per year). Also the mortality related to anthropogenic NO_x-VOC emissions in ROW increases by 17 % in the same period (+1000 deaths per year). On the contrary, a measurable decrease is observed in the mortality attributable to anthropogenic NO_x-VOC emissions in UNECE which drops from 16 000 in 2020 to 14 000 in 2050.

The contributing sectors change their relative importance evolving from a mix dominated by transport, agriculture and energy production in 2020 to a one dominated by agriculture, waste management, transport and energy production in 2050 (Fig. 5, Table S1). Transport, industry and maritime contribute to O₃ exposure only via NO_x-VOC precursors while agriculture, gas flaring and waste management contribute almost only via CH₄ emissions (Fig. S3).

The CH₄ impact of agriculture, gas flaring, waste management and energy production emissions from ROW on O₃ exposure in UNECE presents an upward trend between 2020 and 2050 (Fig. S3). In the same time window, the NO_x-VOC contribution from transport, energy production and domestic emissions from UNECE show a downward trend with the exception of industry which increases slightly. Although energy production is the only source which shares of O₃ exposure due to NO_x-VOC and CH₄ are comparable, the balance between these two components evolves along the studied time window towards an increase in the share of the latter.

3.4 Source allocation of PM_{2.5} exposure and premature mortality in UNECE in the baseline scenario

The UNECE anthropogenic emissions are the main responsible for PM_{2.5} exposure in UNECE, with a decreasing trend between 2020 and 2050, while those from ROW have a minor role which increases slightly over the observed time window (Fig. 6).

The mortality associated with PM_{2.5} exposure in the UNECE region (including both natural and anthropogenic sources) is 444 000 cases in 2020. It shows a downward trend between 2020 and 2030 and a subsequent rise between 2040 and 2050 when it reaches 443 000 units (Fig. 6b).

The main anthropogenic contributors within UNECE are agriculture, industry, domestic, energy production and transport (Fig. 7, Table S2). An overall downward trend in the impact of domestic, energy production and transport from UNECE and an increasing role of industry and agriculture from

this region are observed. The share of maritime, a contributor which is not geographically allocated in this analysis, is stable from 2020 onwards. In 2050, there is an increase in the PM_{2.5} exposure mainly due to a rise in the impact of agriculture, transport, gas flaring and waste management emissions from ROW, and there is an increase of agriculture and industry emissions from the UNECE region.

3.5 Source allocation of exposure to air pollutants in UNECE in MFR scenarios

This section evaluates the trends of the O₃ and PM_{2.5} exposure in UNECE between 2020 and 2050 computed with TM5-FASST using the ECLIPSE V6b MFR BASE and MFR-SDS emission scenarios (Table A1; Fig. 8). In 2050, the MFR BASE and MFR-SDS O₃ exposure is 16 % and 20 % lower than CLE, respectively, while the PM_{2.5} (anthropogenic) exposure in the above-mentioned scenarios is 51 % and 59 % below CLE, respectively.

In the period 2025–2050, the main anthropogenic contributor to O₃ exposure and mortality in both MFR scenarios is by far agriculture due to CH₄ emissions in ROW (Fig. S4).

In the MFR BASE scenario, which is mainly based on the implementation of best available technologies (BATs) and Paris Agreement NDCs, the delta mortality in UNECE compared to CLE ranges from –13 000 cases (–21 %) in 2025 to –24 000 cases (–34 %) in 2050 due to lower O₃ exposure (Fig. 9a). Such an improvement is mainly associated with NO_x-VOC emission reductions in the UNECE region and reductions of CH₄ in ROW, the role of which increases considerably between 2025 and 2050 (Fig. 9a). A more detailed analysis of the MFR BASE reveals that the main UNECE NO_x-VOC emission reductions in 2050 are associated with energy production, industry and transport sectors. By comparison, those of CH₄ in ROW are mainly due to abatement of gas flaring and energy production in 2025 with dramatic abatement increase in the waste management sector between this year and 2050 (Fig. 10a and b).

The additional improvement compared to the MFR BASE from the most ambitious MFR-SDS scenario, in line with energy related SDGs and global temperature increase containment, ranges between ca. –2000 cases (–4 %) in 2025 and –5500 (–11 %) cases in 2050, and it is mainly due to the reduction of NO_x-VOC emissions in both UNECE and ROW (Fig. 9c). Such abatement of O₃-related mortality in the MFR-SDS scenario is associated with emission reductions in the transport sector in 2050 in both UNECE and ROW compared to 2020 (Fig. 10c and d).

In MFR BASE, the delta mortality in UNECE due to PM_{2.5} exposure compared to the CLE ranges from ca. –137 000 cases (–33 %) in 2025 to ca. –187 000 cases (–41 %) in 2050 (Fig. 9b). Such an improvement is mainly due to abatement of emissions in the agriculture and industry sectors in UNECE. In this region, the abatement of emissions in the domestic sector shows a decreasing impor-

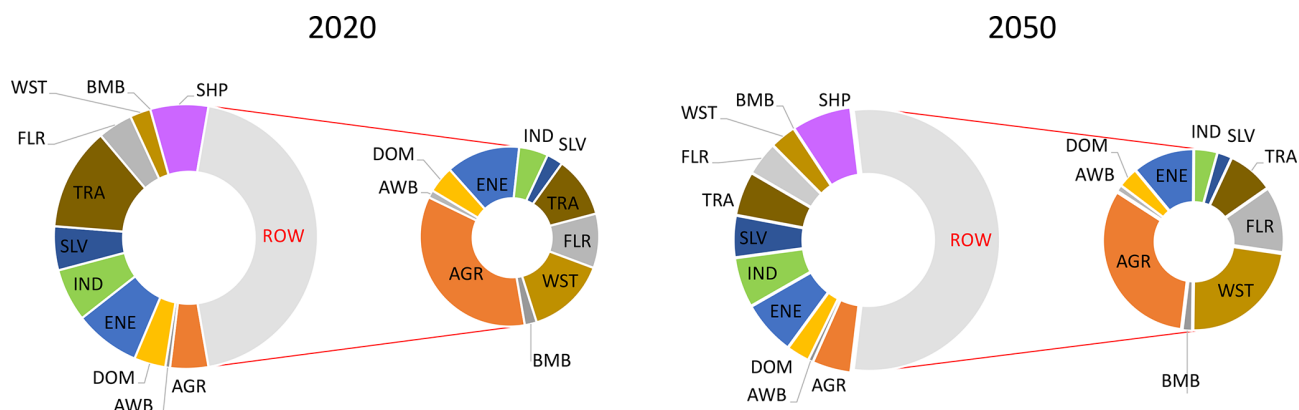


Figure 5. Allocation of O₃ exposure and related mortality (UNECE avg.) to anthropogenic sources under CLE. The overall impacts are represented in the main pie charts while the small pie charts to the left of them show the detail of ROW impacts only. The data are also available in Table S1 in the Supplement. AGR: agriculture, AWB: agricultural waste burning, DOM: domestic and commercial combustion, ENE: energy production, IND: industry, SLV: use of solvents, TRA: road transport, FLR: gas flaring, WST: waste management, BMB: open biomass burning and SHP: maritime.

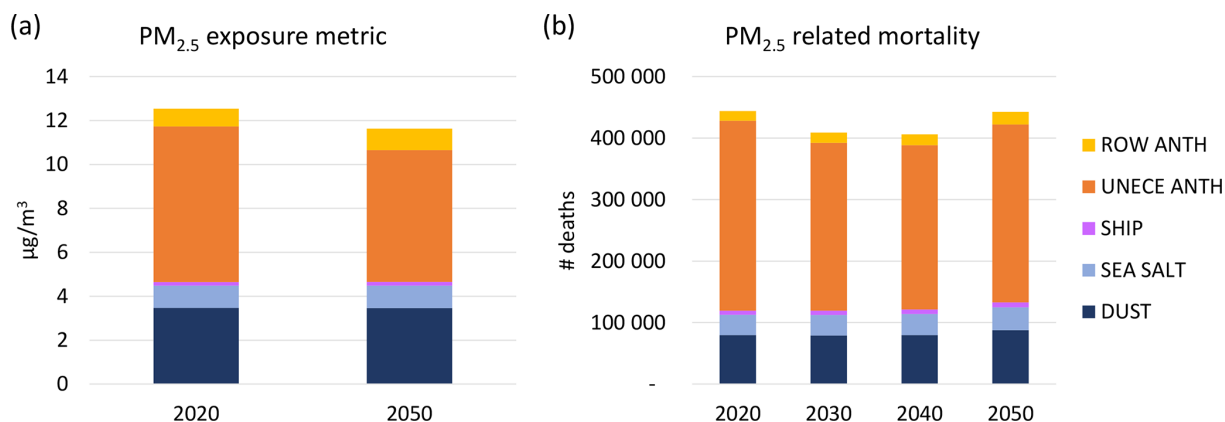


Figure 6. (a) Allocation of the population weighted PM_{2.5} exposure in UNECE to geographic source areas (UNECE, ROW) and natural sources under CLE. (b) Mortality (UNECE average) associated with PM_{2.5} exposure attributable to both anthropogenic and natural sources under CLE.

tance between 2025 and 2050 while the opposite is true for agricultural waste burning and the anthropogenic emissions in ROW. By comparison, the MFR-SDS scenario leads to an additional reduction in mortality compared to the MFR BASE of ca. $-19\,000$ cases (-7%) in 2025 that reaches ca. $-40\,000$ cases (-15%) in 2050 (Fig. 9d). In this case, the reduction is associated with abatement of industry emissions, relatively constant throughout the observed period, and an increasing abatement along the studied time window in domestic and transport sectors from UNECE and anthropogenic emissions in ROW (Fig. 9d).

4 Main findings and discussion

The implementation of more stringent air quality and GHG emission abatement policies only in the UNECE region (MFR UNECE scenario) leads to limited benefits in the air

pollution exposure in this region because their effect is partially offset by the unabated emissions from non-UNECE countries, when similar measures are not implemented there as well. Such an effect is more pronounced for O₃ than for PM_{2.5}.

In CLE, the main single contributor to the O₃ exposure in the UNECE region is non-anthropogenic O₃ (other/natural), including biogenic and other unspecified sources (mainly soil-derived NO_x, lightning and stratospheric intrusion), which remains relatively constant at ca. 35 ppb throughout the entire time window (2020–2050). In this scenario, the anthropogenic fraction of the O₃ exposure is equivalent to 16–19 ppb. Transport, industry and maritime sectors contribute to this fraction predominantly via the emissions of NO_x–VOC precursors while agriculture, gas flaring and waste management mostly contribute via emissions of the CH₄ precursor. Energy production is the only source affect-

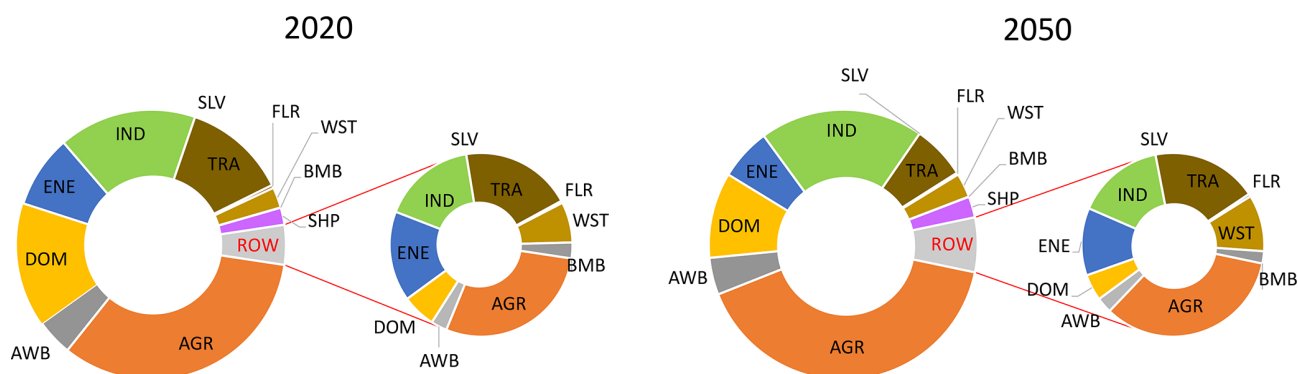


Figure 7. Allocation of $\text{PM}_{2.5}$ exposure and related mortality (UNECE average) to anthropogenic sources under CLE. The overall impacts are represented in the main pie charts while the small pie charts to the left of them show the detail of ROW impacts only. The data are also available in Table S2. AGR: agriculture, AWB: agricultural waste burning, DOM: domestic and commercial combustion, ENE: energy production, IND: industry, SLV: use of solvents, TRA: road transport, FLR: gas flaring, WST: waste management, BMB: open biomass burning and SHP: maritime.

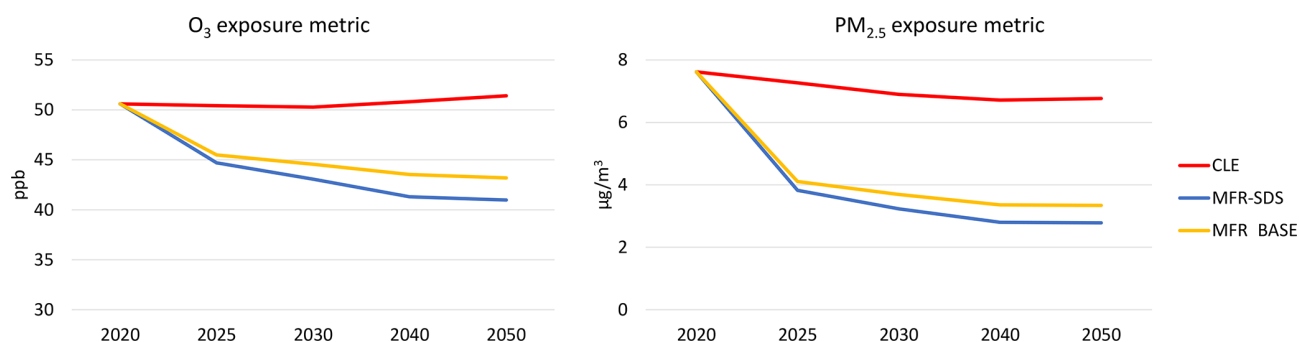


Figure 8. O_3 and anthropogenic $\text{PM}_{2.5}$ exposure metrics (UNECE average) computed with TM5-FASST according to the ECLIPSE V 6b scenarios: CLE, MFR BASE and MFR-SDS.

ing O_3 exposure with similar shares for both precursor families.

The overall upward trend in the O_3 -related mortality in the UNECE region over the studied time window is mainly associated with the increasing share of CH_4 emissions from ROW. The O_3 exposure shares of agriculture, waste management, gas flaring and energy production CH_4 emissions from ROW show an upward trend along the simulated time window while that of transport, energy production and domestic NO_x -VOC emissions from UNECE show an opposite trend.

Unlike O_3 , anthropogenic UNECE emissions are the main source of $\text{PM}_{2.5}$ exposure and related mortality in UNECE countries. However, due to a reduction in the share of UNECE emissions and an increase in that from ROW, the importance of the former decreases from 70 % to 65 % of the total $\text{PM}_{2.5}$ exposure metric over the simulated time window.

As a whole, the MFR BASE leads to 34 % and 41 % mortality reductions compared to the CLE scenario in 2050 for O_3 and $\text{PM}_{2.5}$ exposure, respectively, while the MFR-SDS leads to a total abatement of mortality in 2050 compared to CLE of 41 % and 50 % for O_3 and $\text{PM}_{2.5}$ exposure, respectively.

The applied methodology, based on a reduced form model, has several limitations we discuss here. Some of the limitations are inherited from the parent TM5 CTM. This is the case for secondary organic aerosol chemistry which is not considered and leads to a conservative estimate of $\text{PM}_{2.5}$ exposure and consequently of the benefits from controls. The omission of secondary organic PM in TM5 is estimated to introduce a low bias in the $\text{PM}_{2.5}$ concentration in the order of $0.1 \mu\text{g m}^{-3}$ as global mean. However, regional levels in central Europe and China can reach up to $1 \mu\text{g m}^{-3}$ in areas where average levels of primary organic matter are $20 \mu\text{g m}^{-3}$ (Van Dingenen et al., 2018). In addition, the TM5-FASST model does not include non-linear responses due to changing chemical regimes when switching off individual precursor emissions, nor does it consider impacts of future climate change on photolysis rates and on natural emissions that may affect ozone chemistry. Although an evaluation of climate–chemistry interactions is beyond the capabilities and the scope of the TM5-FASST model, we briefly discuss their possible impacts on our conclusions. The interaction between pollution and climate is complex as it involves many processes: meteorology, precursor emissions

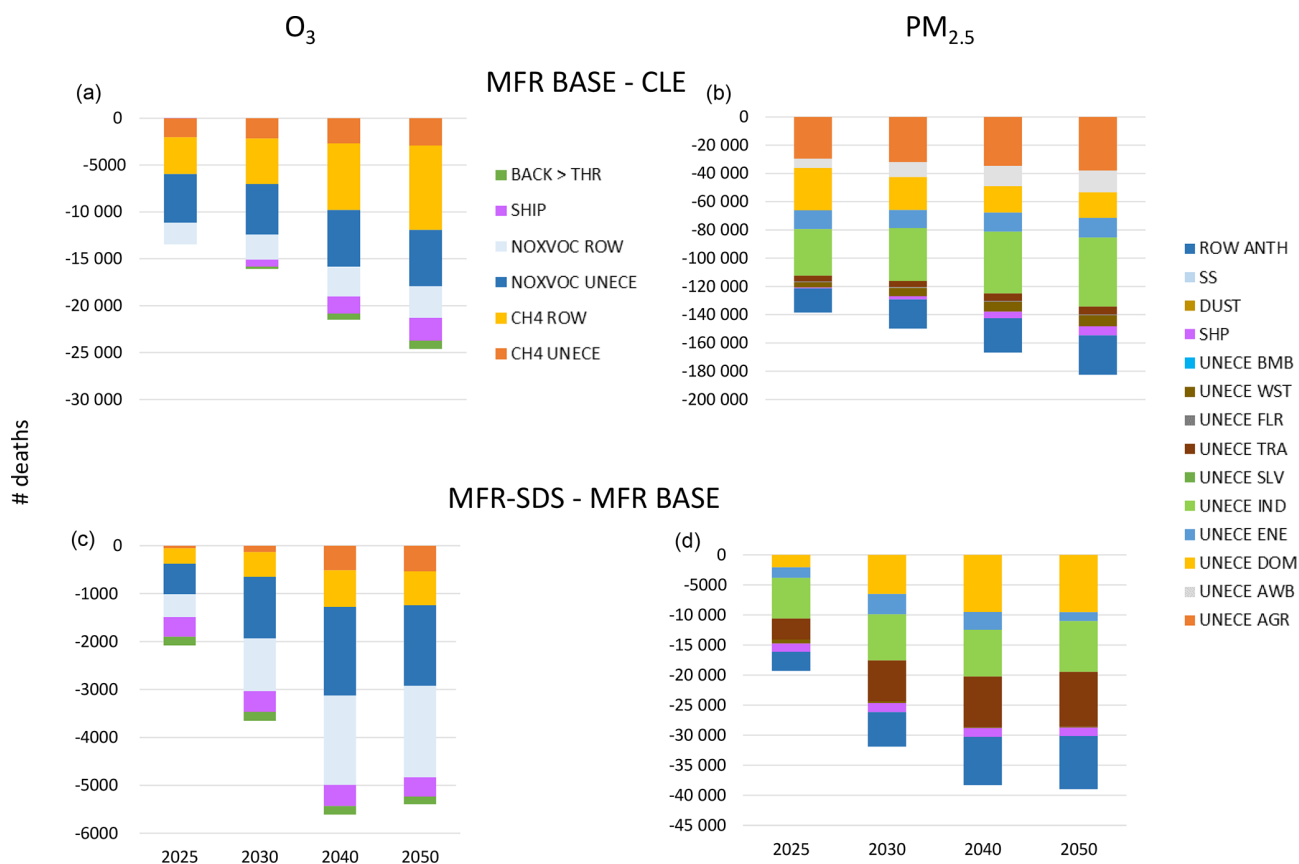


Figure 9. Delta MFR BASE–CLE and MFR-SDS–MFR BASE of O_3 - (a, c) and $PM_{2.5}$ - (b, d) associated mortality (UNECE total) split by precursor and main emission areas. For O_3 we only consider the fraction of “OTHER/NATURAL” exceeding the zero effect threshold of 29.1 ppb.

and atmospheric chemistry, the interactions of which introduce a considerable degree of uncertainty. For instance, the O_3 level derives from the emission of precursors (NO_x and VOC including methane), the interplay of which determines the chemical regime (NO_x -limited or VOC-limited), and is modulated by temperature. From a purely meteorological point of view, a warmer climate is expected to cause a higher frequency of stagnant conditions leading to higher surface ozone production due to higher photolysis rates which would call for more stringent controls than anticipated under present climate in order to meet limit levels. Such climate penalty on summertime surface ozone concentrations is estimated to be in the range of 1–10 ppb, with the highest impacts in polluted conditions (Jacob and Winner, 2009). However, precursor emission reductions may decouple the long-term trends of O_3 summer maximum concentrations and temperature (Fiore et al., 2015).

Natural VOC emissions from vegetation are expected to increase with increasing temperature – up to a critical level after which emissions decrease again (e.g. 38 °C for isoprene). Moreover, the VOC emissions are species-specific and therefore subject to changes due to type of vegetation

or land use variations (Wu et al., 2012). In NO_x -saturated (VOC-limited) conditions (typical of urban polluted areas), the climate-driven increased VOC emissions would increase the natural component of O_3 formation and drive the chemical regime more towards the NO_x -limited region, implying a higher response of O_3 to anthropogenic NO_x emission changes. However, under the more common conditions of VOC saturation (NO_x limitation), the O_3 response to NO_x is only weakly dependent on the VOC concentrations (Akiyama and Tanimoto, 2022).

A warming climate is also expected to increase CH_4 emissions from wetlands, the major natural CH_4 source (Gedney et al., 2004); however, the magnitude of such variation is still quite uncertain (Nisbet, 2023).

The applied TM5-FASST methodology, not including these climate–chemistry feedbacks, is likely to underestimate the natural component of O_3 formation in a future, warmer climate, as well as the O_3 response to NO_x reductions in specific polluted conditions. However, this does not compromise our conclusion that control of anthropogenic CH_4 emissions can play a prominent and increasing role in the coming decades.

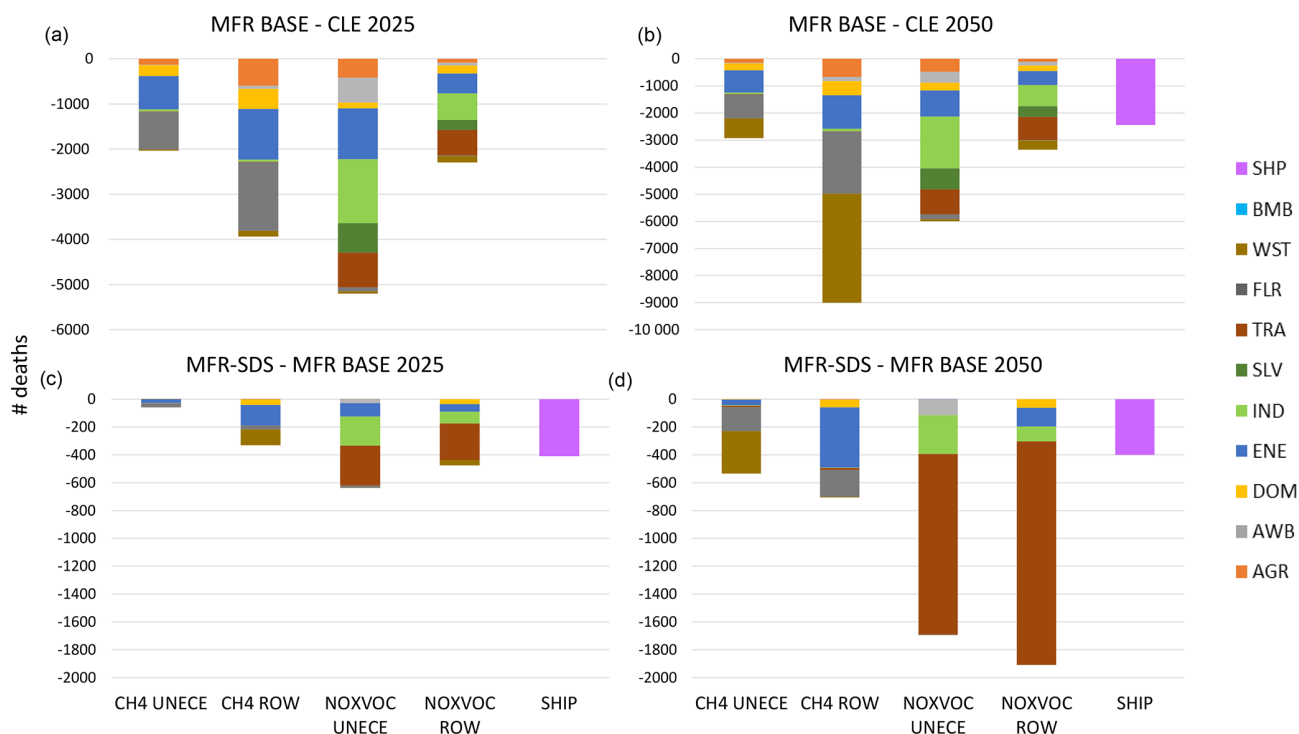


Figure 10. Delta MFR BASE–CLE (a, b) and MFR-SDS–MFR BASE (c, d) of UNECE O_3 -associated mortality in 2025 and 2050 split by source sectors.

The estimated levels and source allocation in our study are comparable with those obtained in studies with similar scope. However, using previous studies as reference is not straightforward due to different underlying methodological assumptions and aggregation of the output data. This is particularly true when comparing the source apportionment with brute-force or emission reduction impact approach (used in this study) with the one resulting from tagged method studies (Appendix A, Fig. A2).

5 Conclusions

The scenario analysis presented in this study assesses the exposure to O_3 and $PM_{2.5}$ and associated mortality between 2020 and 2050 in the UNECE countries. To that end, a baseline scenario in which the air quality and GHG abatement measures adopted by 2018 are implemented (CLE) is compared with other scenarios with increasing degree of ambition. The adopted methodology for the identification of geographic origin with sectoral anthropogenic sources and precursor detail led to an in-depth understanding of the impact that different measures may have on mortality in the UNECE region in the medium and long term.

The study demonstrates that applying emission reductions only in UNECE countries leads to a limited abatement in the O_3 exposure in UNECE countries with respect to the baseline (CLE) and that the implementation of BATs world-

wide would not only lead to higher abatement of exposure in UNECE countries but also to a trend reversal, from increasing to decreasing. Moreover, the study shows that the overall upward trend in the O_3 -related mortality in the UNECE region over the studied time window is mainly associated with the growing share of CH_4 emissions from ROW. This is mostly related to the relatively long atmospheric lifetime of O_3 (compared to $PM_{2.5}$), formed from its short-lived precursors NO_x and NMVOC, and to the one of its long-lived precursor CH_4 which contributes to global background O_3 . On the contrary, $PM_{2.5}$ -related mortality in UNECE appears to be mainly affected by its own emissions.

Controlling O_3 exposure in UNECE countries is necessary to prevent the CLE projected increase in annual mortality from ca. 65 000 in 2020 to ca. 73 500 in 2050 (+9000 deaths per year), while acting on $PM_{2.5}$ is a high priority to avoid the considerable mortality attributed to this pollutant turning back in 2050 to the same levels of 2020 (ca. 444 000 units). The analysis of the CLE scenario suggests the opportunity to act on CH_4 sources agriculture, energy production, gas flaring and waste management beyond the UNECE region (ROW) in order to prevent an increase in O_3 exposure and related mortality in the UNECE countries from 2030 onwards (in addition to the benefits for the ROW region). On the contrary, to significantly reduce the $PM_{2.5}$ exposure and related mortality in the UNECE region beyond the CLE measures in the long term (2050), the main focus

should be on the anthropogenic emissions from agriculture and industry sectors within the UNECE region.

In MFR-SDS, the abatement of some of the most critical CH₄ sources identified in the analysis of CLE (energy production, gas flaring and waste management) plus the reduction of NO_x-VOC from industry and transport globally and those of the maritime sector lead to a 30%–41% drop of O₃-related mortality with respect to CLE in 2030 and 2050 (equal to ca. 20 000–30 000 avoided premature deaths per year), respectively. Moreover, the abatement of the most critical UNECE PM_{2.5} emissions identified in the analysis of CLE (i.e. agriculture and industry) plus emissions in the domestic sector complemented by reductions in natural sources (DUST and SS) lead to a 44%–50% drop in the PM_{2.5}-related mortality compared to CLE in 2030 and 2050 (equal to ca. 182 000–221 000 avoided premature deaths per year), respectively.

The analysis of the MFR-SDS scenario confirms that the measures in line with UN's SDGs concerning energy sources can lead to significant benefits. It also shows the potential co-benefits of joint air quality and GHG abatement policies in line with the Paris Agreement ambition of keeping the global average temperature increase below 2 °C. However, considering the impact of agriculture, an important NH₃ contributor, on the two studied pollutants in the CLE scenario, more ambitious reductions of this source should be explored, considering that the abatement of NH₃ in the MFR scenarios compared to CLE is modest (–32% to –35% in UNECE in the studied time window).

The conclusions of this study are relevant for the revision of the UNECE's Air Convention Gothenburg protocol.

Appendix A

Comparison with other studies

The source allocation of average PM_{2.5} exposure in UNECE described in the present study is comparable with the one reported by Mc Duffie et al. (2021) for all world countries in 2017 on the basis of a combination of satellite data, chemical transport models and ground-based observations. The UNECE average population-weighted PM_{2.5} split in 20 source categories including fuel details obtained from the country averages reported in the above-mentioned study is shown in Fig. A1a. Such categories are merged using the same categories as the present study for comparison with the estimations obtained with TM5-FASST extrapolated for 2017 (Fig. A1b).

The average UNECE population-weighted PM_{2.5} from TM5-FASST is 2.4 µg m⁻³ (–18%) lower than the one obtained from the country values reported by Mc Duffie and co-authors, likely due to the use of data fusion in the latter. The population-weighted PM_{2.5} allocated by TM5-FASST to energy production and domestic is lower than the one reported in the above-mentioned study (–47% and –29%, respec-

tively). On the contrary, the higher agricultural waste burning share in TM5-FASST (+160%) has been attributed to the incorporation of forest fires under this category in this model (Fig. A1b).

The UNECE O₃ source allocation in the 2010 warm season (April–September) obtained in this study with TM5-FASST based on a perturbation approach was compared with the one reported by Butler et al. (2020) using a tagging approach (hereon Butler2020). Comparing the O₃ apportionment in these studies is, however, not straightforward because Butler2020 splits the total O₃ concentrations in two alternative ways by either NO_x precursors or VOC precursors while TM5-FASST splits them between NO_x-VOC and CH₄ precursors at once. Moreover, in Butler2020, Central Asia (CAS) VOC contributions as well as those from Israel are included in ROW, while in this study, these countries have been included in the UNECE region.

The O₃ concentrations are higher in TM5-FASST compared to Butler2020, likely due to the use of maximum daily 8 h averages instead of monthly averages (Fig. A2). The share of O₃ produced by NO_x-VOC emitted in UNECE according to TM5-FASST (6 ppb, 13%) lies in-between the estimations obtained by Butler2020 for the contribution of NO_x (17 ppb, 45%) and NMVOC (4 ppb, 10%) emissions in this region. By comparison, the share of O₃ derived from NO_x-VOC emissions from ROW provided by TM5-FASST (2 ppb, 4%) is slightly lower than the estimations by Butler2020 for NO_x (4 ppb, 11%) and VOC (3 ppb, 7%), respectively.

Butler2020 links the CH₄-related O₃ only to VOC emissions and does not associate this precursor to any specific geographic area, while TM5-FASST allocates CH₄-related O₃ to its geographic source regions and precursors. In this analysis, the TM5-FASST aggregated share of O₃ associated with CH₄ (6 ppb, 13%) is considerably lower than the one attributed by Butler2020 to this fraction (13 ppb, 35%). Also, the contribution of shipping to O₃ concentrations estimated by Butler2020 (4 ppb, 10%) is higher than the share reported by TM5-FASST in this study (1 ppb, 2%). By comparison, the role of the other/natural source is higher in TM5-FASST (35 ppb, 67%) compared with the one attributed by Butler2020 (13 ppb, 33% for NO_x and 18 ppb, 48% for VOC source allocation, respectively).

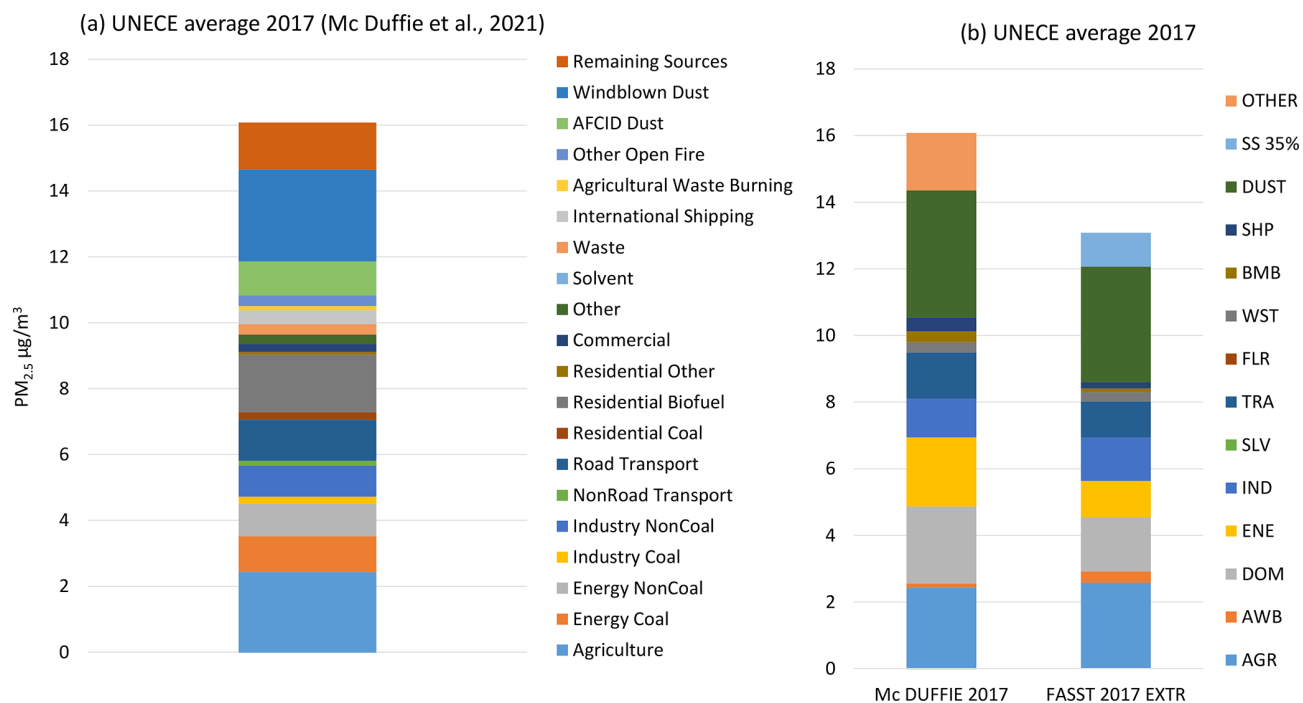


Figure A1. UNECE average population-weighted $PM_{2.5}$ split by source categories. (a) Original source categories (Mc Duffie et al., 2021); (b) comparison of $PM_{2.5}$ source apportionment of the present study with the one by Mc Duffie et al. (2021) using the same source categories.

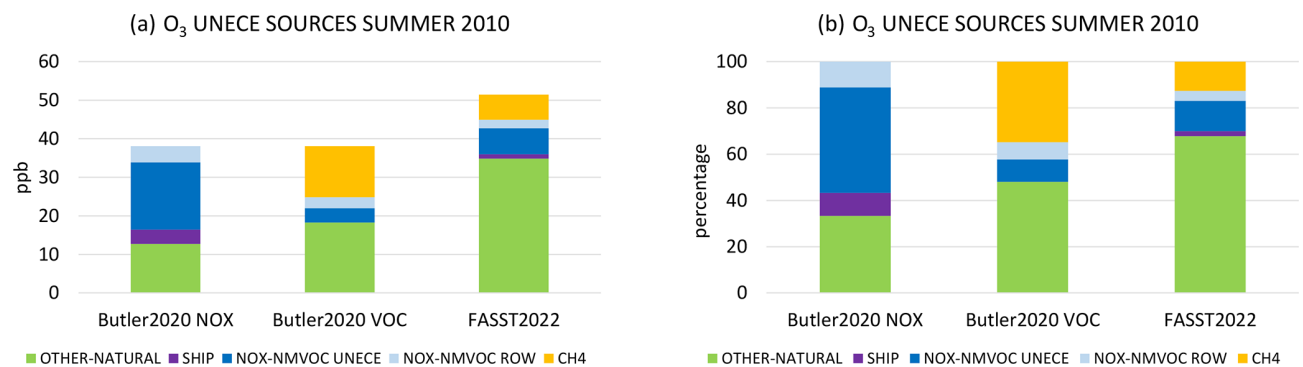


Figure A2. UNECE average O_3 split by source categories using a tagged approach (Butler et al., 2020) and a perturbation approach (TM5-FASST, this study) expressed as concentrations (a) and percentages (b).

Brief description of scenarios

The scenarios used in this study are summarized in Table A1.

Table A1. Description of the ECLIPSE version 6b global scenarios used in this study (IIASA, 2021).

Scenario	Abbreviation	Air quality policy	Climate policy
Current legislation (baseline)	CLE	Assumes the implementation of the future commitments included in the air quality legislation in force by 2018. Current baseline projections according to the IEA World Energy Outlook 2018 New Policy Scenario (NPS) which includes EU 2030 renewable energy and energy efficiency targets and announced energy policies by China, USA, Japan and Korea.	Incorporates only commitments made in the national determined contributions (NDC) under the Paris Agreement.
Maximum technical reduction baseline	MFR BASE	Stringent policy assuming introduction of best currently available technology and no-cost limitations. However, no further technological improvements are foreseen. Same activity drivers as CLE following NPS.	Incorporates only commitments made in the NDCs under the Paris Agreement.
Maximum technical reduction sustainable development	MFR-SDS	Similar to MFR BASE. However, relies on the most ambitious IEA Sustainable Development Scenario (SDS). Includes outcomes of energy-related Sustainable Development Goals (SDGs): dramatically reducing premature deaths due to energy-related air pollution and universal access to modern energy by 2030.	Aligned with Sustainable Development Goal #13 and Paris Agreement goal of holding global average temperature increase below 2 °C.

The current legislation baseline (CLE) scenario considers fuel consumption from IEA (International Energy Agency), agriculture data from FAO (UN Food and Agriculture Organization) and IFA (International Fertilizer Organization), and statistics on industry, waste, shipping, etc. from other sources (IEA, 2018).

Code and data availability. The FASST code is available at <https://doi.org/10.5281/zenodo.7417835> (Sampe dro et al., 2022). Data used in this work are available at <https://doi.org/10.5281/zenodo.8077436> (Belis and Van Dingenen, 2023).

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