Reducing future air pollution-related premature mortality over Europe by mitigating emissions: assessing an 80% renewable energies scenario

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Abstract. Worldwide air quality has worsened in the last decades as a consequence of increased anthropogenic emissions, in particular from the sector of power generation. The evidence of the effects of atmospheric pollution (and particularly fine particulate matter, PM2.5) on human health is unquestionable nowadays, producing mainly cardiovascular and respiratory diseases, morbidity and even mortality. These effects can even enhance in the future as a consequence of climate penalties and future changes in the population projected. Because of all these reasons, the main objective of this contribution is the estimation of annual excess premature deaths (PD) associated to PM2.5 on present (1991-2010) and future (2031-2050) European population by using non-linear exposure-response functions. The endpoints included are Lung Cancer (LC), Chronic Obstructive Pulmonary Disease (COPD), Low Respiratory Infections (LRI), Ischemic Heart Disease (IHD), cerebrovascular disease (CEV) and other Non-Communicable Diseases (other NCD). PM2.5 concentrations come from coupled chemistry-climate regional simulations under present and RCP8.5 future scenarios. The cases assessed include the estimation of the present incidence of PD (PRE-P2010), the quantification of the role of a changing climate on PD (FUT-P2010) and the importance of changes in the population projected for the year 2050 on the incidence of excess PD (FUT-P2050). Two additional cases (REN80-P2010 and REN80-P2050) evaluate the impact on premature mortality rates of a mitigation scenario in which the 80% of European energy production comes from renewables sources. The results indicate that PM2.5 accounts for nearly 895,000 [95% confidence interval (95% CI) 725,000-1,056,000] annual excess PD over Europe, with IHD being the largest contributor to premature mortality associated to fine particles in both present and future scenarios. The case isolating the effects of climate penalty (FUT-P2010) estimates a variation +0.2% on mortality rates over the whole domain. However, under this scenario the incidence of PD over central Europe will benefit from a decrease of PM2.5 (-2.2 PD/100,000 h.) while in eastern (+1.3 PD/100,000 h.) and western (+0.4 PD/100,000 h.) Europe PD will increase due to increased PM2.5 levels. The changes in the projected population (FUT-P2050) will lead to a large increase of annual excess PD (1,540,000, 95% CI 1,247,000-1,818,000), +71.96% with respect to PRE-P2010 and +71.67% to FUT-P2010) due to the aging of the European population. Last, the mitigation scenario (REN80-P2050) demonstrates that the effects of a mitigation policy increasing the ratio of renewable sources

in the energy mix energy could lead to a decrease of over 60,000 (95% CI 48,500-70,900) annual PD for the year 2050 (a decrease of -4% in comparison with the no-mitigation scenario, FUT-P2050). In spite of the uncertainties inherent to future estimations, this contribution reveals the need of the governments and public entities to take action and bet for air pollution mitigation policies.

1 Introduction

Air pollution is nowadays a leading cause of global disease burden, especially in low- and middle-income countries (Balakrishnan et al., 2019), and is expected to greatly increase under future climate scenarios (e.g. Fang et al. (2013a); Tarín-Carrasco et al. (2019); Park et al. (2020), among others). Fine particulate matter (PM2.5) is a common air pollutant with important effects on human health. Exposure to this pollutant leads to cardiovascular or respiratory diseases, together with an increase in premature mortality (e.g. (Brook et al., 2010; Evans et al., 2013; Hamra et al., 2014; Ford and Heald, 2016; Im et al., 2018; Tarín-Carrasco et al., 2019), among others). Short- or long-term exposure to PM2.5 can have different impacts on human health. The much larger effects of long-term exposition may suggest that the effects on human health are not only due to increased pollution, but also to the progression of underlying diseases (World Health Organization, 2013).

In addition, over 90% of the population who lives in cities is exposed to this pollutant in concentrations exceeding the air quality guidelines stablished by Word Health Organization (WHO) (Prüss-Üstün et al., 2016). Lelieveld et al. (2013) estimate that 69% of the global population is exposed to an annual mean anthropogenic PM2.5 concentration >10 μg m^{-3} (WHO air quality guideline); 33% to concentrations over 25 μg m^{-3} (limit value of EU Directive 2008/50/CE); and 20% to concentrations >35 μg m^{-3}, the WHO Level 1 Interim Target (World Health Organization, 2013). Focussing on Europe for present scenarios, Lelieveld et al. (2013) calculate global respiratory mortality incidence associated to air pollution as 773,000 per year, 186,000 by lung cancer and 2,000,000 by cardiovascular disease. For Europe, Andersson et al. (2009) estimate the number of excess premature deaths (PD) in 301,000 per year caused by the same pollutant.

Nowadays, the contribution of anthropogenic PM2.5 to the globally mortality is around 70% (Silva et al., 2016a), with some hotspots in East Asia, India and Europe. However, mortality attributable to air pollution has changed over the last 25 years (Fang et al., 2013a; Silva et al., 2013; Cohen et al., 2017). Silva et al. (2013) attribute these increases in mortality to direct changes in anthropogenic emissions and estimates that 2.1 million of Chronic Obstructive Pulmonary Disease (COPD) and Lung Cancer (LC) premature deaths are related to PM2.5. In addition, these numbers are expected to increase under future climate scenarios as a consequence of the effect of the *climate penalty* on air quality (Silva et al., 2016b; Hong et al., 2020; Park et al., 2020). Climate change will modify air quality by altering physico-chemical processes and parameters such as temperature (and thus the oxidative capacity of the atmosphere), wet deposition or dynamical changes (Jacob and Winner, 2009; Jiménez-Guerrero et al., 2013a).

Despite fine particulate matter can travel long distances, provoking the increase of mortality in a global scale, Anenberg et al. (2014) estimate that 93%-97% of PD associated to air pollution occur within the source region. Therefore, the contribution of anthropogenic emissions to air pollution is remarkable. As estimated by Fang et al. (2013a), the 95% of mortality from PM2.5

is driven by local emissions of short-lived air pollutants and their precursors. The main source of emissions responsible for these numbers differs among regions. In Europe, despite agriculture is the sector with a higher contribution to PM2.5 emissions (Lelieveld et al., 2015; Crippa et al., 2019), the sources responsible for the largest impact on PD linked to outdoor air pollution are land traffic and energy use (Lelieveld et al., 2015; Silva et al., 2016a).

60   Therefore, the implementation of mitigation controls and environmental policies that can help offsetting the effect of climate penalty become essential for reducing premature mortality over Europe (McConnell et al. (2006); Anenberg et al. (2014); Fang et al. (2013); Crippa et al. (2019), among others). Changes in future anthropogenic emissions will depend on different variables; such as socioeconomics, technology and developments, energy demand, demographic trends and land use change, as well as climate policies (Kirtman et al., 2013). In this sense, Silva et al. (2016a) suggested that specific actions targeting

65 in residential and commercial sectors can control the emissions on PM2.5 and would benefit human health. Other works, as those of Anenberg et al. (2014) or Liang et al. (2018) showed that reducing anthropogenic emissions by 20% can substantially decrease the incidence of excess mortality. Under a business as usual scenario (no emission control), the contribution of outdoor pollution to PD could increase by 100% by the mid-century, doubling in 2050 (Lelieveld et al., 2015). In this line, Lelieveld et al. (2019) showed that replacing fossil fuels by renewable energy sources could improve the numbers related to the loss of

70 life expectancy from air pollution. However, previous studies have shown that e.g. an aging population in the future, have the potential to counteract the effect of these emission reductions (Geels et al., 2015).

    Hence, the objective of this study is to estimate the present (1991-2010) incidence of excess PD (PD per year) associated to fine particulate matter and their changes under several future scenarios for the years 2031-2050 that include climate penalty, projected population by 2050 and a mitigation scenario where the 80% of the European energy production comes from re-

75 newable sources. A number of different endpoints or causes of premature mortality as Lung Cancer (LC), Chronic Obstructive Pulmonary Disease (COPD), Low Respiratory Infections (LRI), Ischemic Heart Disease (IHD), cerebrovascular disease (CEV) and other Non-Communicable Diseases (other NCD) is included in this contribution.

2   Methodology and data

2.1   Premature mortality estimation by exposure-response functions

80 Future PD caused by several specific endpoints related to PM2.5 have been estimated using non-linear exposure-response functions, an analogous methodology as that previously implemented in Tarín-Carrasco et al. (2020). The health impact function in each grid has been applied (Equation 1) to estimate premature mortality:

$$\Delta M = y_0 \times \left[\frac{RR - 1}{RR} \right] \times Population \tag{1}$$

    This equation is based on epidemiological relationships between air pollution concentration and mortality in each grid

85 cell, where ΔM is premature mortality due to a specific disease, y_0 is the baseline mortality rate, RR is the risk ratio and $Population$ refers to the exposed population (in this contribution, adults are considered). y_0 varies according to the mortality

cause, age and European region (Figure SM1 in the Supplementary Material) and is estimated by the WHO for each sex and every year. Sex mixing values used in the present study account for both male and female dwellers during the year 2017 (the last available). Premature mortality and RRs has been estimated for each pathology and different group ages included in this

90 contribution: 25-29, 30-34, 35-39, 40-44, 45-49, 50-54, 55-59, 60-64, 65-69, 70-74, 75-79, +80 and all ages.

Risk ratios were determined following the GEMM methodology developed by Burnett et al. (2018) (Equation 2):

$$RR = exp\left[\theta\frac{log[\frac{z}{\alpha}+1]}{(1+exp(-\frac{z-\mu}{\nu}))}\right], where \ z = max(0, PM2.5 - 2.4\mu gm^{-3}) \tag{2}$$

where θ, α, μ and ν are variables obtained from Burnett et al. (2018) for each pathology and z refers to the PM2.5 mean annual concentration. The pathologies included in this work are Lung Cancer (LC), Chronic Obstructive Pulmonary Dis-

95 ease (COPD), Lower Respiratory Infection (LRI), Cerebrovascular Disease (CEV), Ischemic Heart Disease (IHD) and non-accidental diseases (NCD+LRI). "Other NCD" is calculated as the subtraction of NCD+LRI and the rest of the categories. Uncertainty ranges are expressed as the 95% confidence intervals (95% CIs), adopted from Burnett et al. (2018).

2.2 Population data

Population data for Europe has been taken from the NASA SocioEconomic Data and Applications Center (2019) gridded

100 dataset. These data provide the population density by age and gender for the year 2010 consistent with national censuses and population registers with a resolution of 5 km². Population data were interpolated to the working grid to make it consistent with the gridded air pollution data (Figure SM2,top in the Supplementary Material).

With respect to the future population, a projection for the year 2050 has been estimated by using information from the Population Prospects from United Nations Organization (UN) Department of Economic and Social Affairs Population Dy-

105 namics (United Nations, 2020). This includes both a development of the total national numbers but also the age distribution. The relative variation of the population from this dataset between 2010 and 2050 for each European country and age range was calculated in order to obtain the ratio of population for the future scenario (2050) in this study (Figure SM2,bottom in the Supplementary Material). The population pyramid both for the year 2010 and 2050 is presented in Figure 1. This Figure indicates a very slight projected decrease (-0.2%) of the European population (807.5 M vs. 806.2 M dwellers both for present

110 and future population, respectively), especially over Eastern Europe (-4.0%). Conversely, population in Western and Central Europe increases in the UN 2050 projections (+2.7% and +5.7%, respectively). In addition, the projected data includes a higher population density over many urban areas, and a clear aging of the European citizens. As an example, population over 80 years (80+) barely represents 4% of the total European population nowadays, while it is expected to increase to >9% in the projected UN 2050 estimations.

115 2.3 Air quality data and scenarios

The availability of observed air pollution data for conducting studies on the impacts of air pollution on human health is scarce. The network of stations for measuring air pollutants is generally insufficient for health purposes due to their spatial misalign-
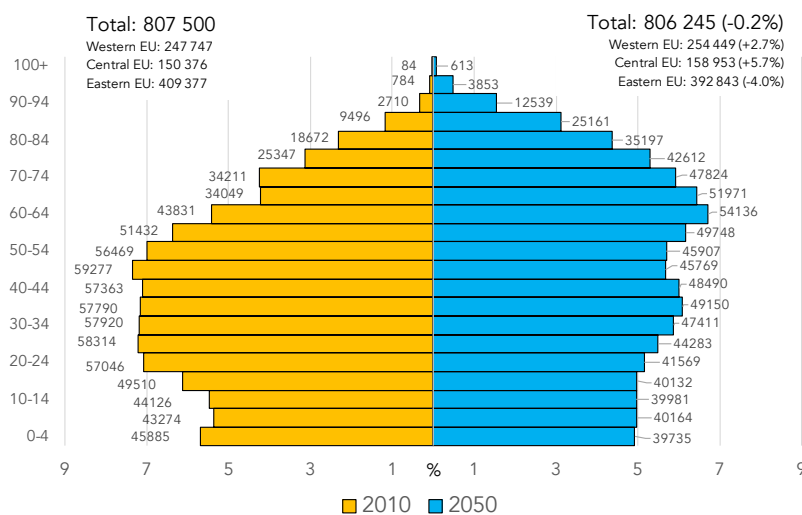
Figure 1. Population pyramid by age range for the year 2010 (orange, left) and 2050 projected by the UN (blue, right). Population data are shown in thousands. x-axis represents the percentage of the contribution of each age range to the total population.

ment and low coverage (Vedal et al., 2017). This limitation leads to the use of modelling outputs for providing information about air pollution, especially if future air quality projections are needed (Tarín-Carrasco et al., 2019).

120   Here, air quality model data from the WRF-Chem model (Grell et al., 2005) under the REPAIR initiative (Palacios-Peña et al., 2020) is used as input to Equation 2 in order to estimate the annual PD associated to different endpoints in both current and future climate change scenarios. The domain covers Europe with a horizontal resolution of $0.11°$ under the Euro-CORDEX requirements (Jacob et al., 2020). For future scenarios, climate forcing is derived from the RCP8.5 scenario, since RCP8.5 represents an upper limit to climate impacts (Moss et al., 2010). The reference periods span 1991-2010 for the present and

125   2031-2050 for the future projections. In order to isolate the possible effects of climate change on pathologies only due to changes in atmospheric pollutants, constant anthropogenic emissions are assumed, from the ACCMIP database (Lamarque et al., 2010). This allows possible impacts to be anticipated if mitigation strategies for regulatory pollutants are not carried out and characterizes the climatic penalty on air quality levels.

    The parameterizations implemented in the WRF-Chem model, together with the model data used for these simulations, has

130   been described and validated in detail in a number of previous contributions (e.g. Tarín-Carrasco et al. (2019), Jerez et al. (2020) or Palacios-Peña et al. (2020), among others). This information is summarized in Table SM1 of the Supplementary Material.

2.3.1 Emissions scenarios

As aforementioned, anthropogenic emissions come from the ACCMIP initiative (Lamarque et al., 2010). Taking those emis-
135 sions as basis, a scenario where emissions from the energy sector in the future have been mitigated is defined, based on the
European 2050 Roadmap (European Climate Foundation, 2010) of the European Climate Foundation (ECF). The ECF sets
three possible scenarios in their strategy for the year 2050, which differ on the percentage of renewable energy production
(40%, 60% and 80%) aimed in 2050. Despite complicated, the ECF indicates that the 80% scenario considered here is achiev-
able if the power sector is assumed to implement essentially carbon-free technologies, and hence that emission scenario (from
140 now on, denoted as REN80) has been implemented as a mitigation scenario in this contribution.

Present-day energy production has been estimated from data of the European Environment Agency (2020) with respect to
gross electricity production by fuel (Table 1). For the REN80 scenario, energy production by different energy sectors like coal,
gas and nuclear are taken into account as the 20% of non-renewable energies. The remaining 80% is expected to be produced
from sources such as wind power (representing almost one third of the energy production in 2050 with a percentage of 30%);
145 solar power (23%); biomass and hydropower (12% each); and geothermal, which presents the smallest contribution in 2050
(2%). Figure 2 shows the energy mix by sector for the year 2050 in REN80. For this scenario, the present and future power
production in the target domain is presented in Table 1.
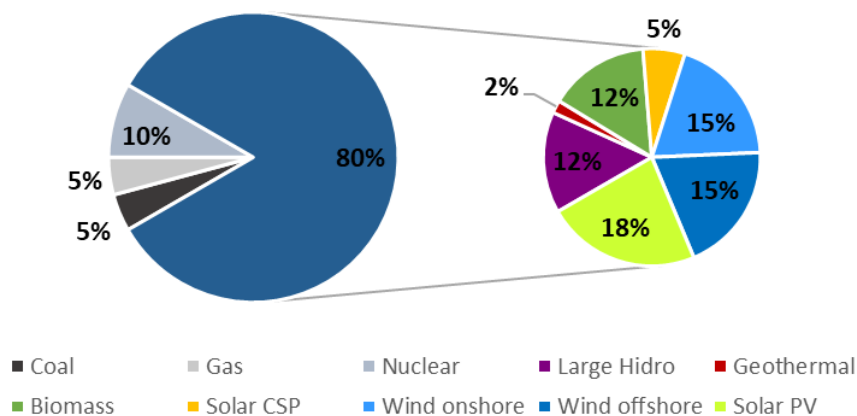
Figure 2. Energy mix in the REN80 scenario for the year 2050.

In order to estimate emissions from energy production, the emission factors were obtained from the EMEP/EEA air pollutant
emission Inventory Guidebook – 2019 (European Environment Agency, 2019). The emission factors from coal (brown, coking,
150 steam, sub-bituminous and hard), natural gas, gaseous fuel, residual oil and gas oil energy production were selected based on
the activity data from Tier 2 method in section 1.A.1.a "Public electricity and heat production" within the chapter 1.A.1. "SNAP
01 Combustion in energy and transformation industries" of "Part B: sectoral guidance chapters". Figure 3 shows the emission
factors for coal, oil and gas. The highest emission factors for CO, NOx and SOx are related to coal (1174 g/GJ; 3,170 g/GJ and

Table 1. Annual energy production (in billion of GJ) over Europe from different sources and contribution to the energy mix in present and REN80 scenario.

	Present	(1991-2010)	Future	(2031-2050)
	GJ $\times 10^9$	%	GJ $\times 10^9$	%
Renewables	5.15	29.23%	14.10	80.00%
Nuclear	4.54	25.80%	1.76	10.00%
Oil	0.32	1.83%	–	–
Coal	3.74	21.25%	0.88	5.00%
Gas	3.48	19.73%	0.88	5.00%
Other fuels	0.38	2.16%	–	–

11,640 g/GJ, respectively), while oil is the most important contributor (per GJ of energy produced) in the case of particulate

155   matter PM10 and PM2.5 (923 g/GJ and 798 g/GJ, in that order) and non-methane volatile organic compounds (436 g/GJ).
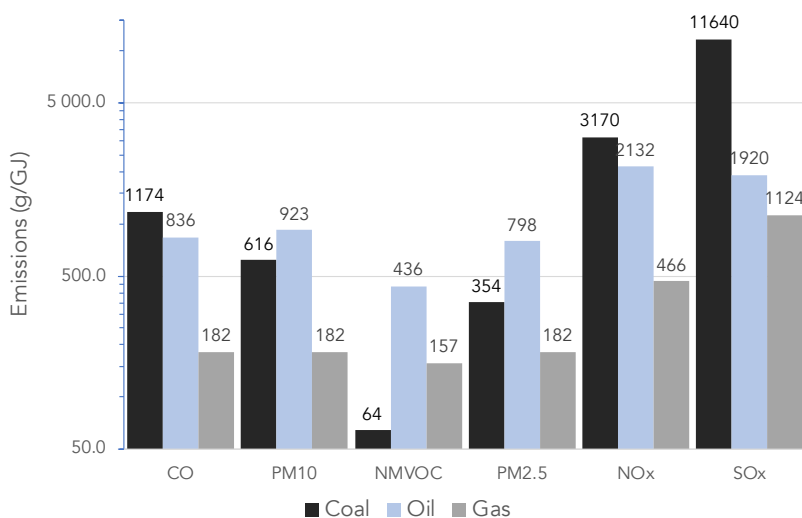
Figure 3. Emission factors (g/GJ) by different type of fuel.

Finally, present and future emissions from the energy sector were estimated following the European Environment Agency (2019) methodology (Equation 3) from the energy produced by each type of fuel and the corresponding emission factor:

$$Emissions = Activity\ Factor\ (GJ) \times Emission\ Factor\ (g/GJ) \qquad (3)$$

The annual mass of pollutants emitted by the different fuels included here (coal and lignite, oil and gas) is shown in Table 2.

160 The estimations indicate that 60 Mtons of emissions of pollutants are annually saved in the REN80 emission scenario compared to the baseline present emissions. Focusing on PM2.5 (the main aim of this contribution), annual emissions decrease from 2.21 Mtons to 0.47 Mtons (reduction of around -79% in the REN80 scenario).

Table 2. Annual ACCMIP emissions of regulatory air pollutants produced by the energy sector used in the simulations (in Mtons) for the SNAP sector representing energy production in the present scenario and projected future emissions under a mitigation scenario taking ACCMIP present emissions as basis.

	Present (1991-2010)	Future (2031-2050)	ΔEmissions
CO	5.30	1.20	-77.4%
NMVOC	0.93	0.20	-78.5%
NOx	14.20	3.21	-77.4%
PM10	3.24	0.70	-78.4%
PM2.5	2.21	0.47	-78.7%
SOx	48.10	11.31	-76.5%
TOTAL	77.29	17.09	-77.9%

2.3.2   Cases for the estimation of present and future premature deaths over Europe

Table 3 compiles the different cases that have been included in this contribution for the estimation of PD associated to PM2.5

165 in Europe. First, the PRE-P2010 case uses present day annual mean concentrations of PM2.5 (1991-2010) and population corresponding to the present period (2010) to estimate PD for baseline conditions. In order to isolate the climate penalty, the FUT-P2010 case uses future concentrations of PM2.5 under the RCP8.5 scenario, keeping population at 2010 levels. Introducing the UN 2050 population changes in the case FUT-P2050 allows estimating the variation of PD caused by modifications in the population pyramid over Europe. Last, REN80-P2010 and REN80-P2050 use the modelled PM2.5 concentrations of

170 pollutants for the future RCP8.5 scenario using REN80 emissions and with population corresponding to the year 2010 and changes for 2050, respectively.

3   Results and discussion

The results presented in this section try to disentangle the impacts of PM2.5 levels over Europe on present and future premature mortality over Europe. For that purpose, a brief description of the changes in PM2.5 concentration as a consequence of the

175 climate penalty are presented. Once these changes are established, the estimation of present PD (PRE-P2010 case) over three different areas of Europe (Western EU, Central EU and Eastern EU) are discussed. Next, the effect of climate penalty on PD is assessed for a future scenario (RCP8.5, 2031-2050) keeping the population constant at 2010 levels (FUT-P2010). The results

Table 3. Summary of cases considered for the estimation of premature deaths over Europe.

Acronym	Period	Forcing	Population	Emissions
PRE-P2010	1991-2010	MPI-M historical*	2010	ACCMIP
FUT-P2010	2031-2050	MPI-M CMIP5 rcp85**	2010	ACCMIP
FUT-P2050	2031-2050	MPI-M CMIP5 rcp85**	2050	ACCMIP
REN80-P2010	2031-2050	MPI-M CMIP5 rcp85**	2010	ACCMIP modified according REN80
REN80-P2050	2031-2050	MPI-M CMIP5 rcp85**	2050	ACCMIP modified according REN80

*Giorgetta et al. (2012a); **Giorgetta et al. (2012b)

for the future case considering also the change on the population for 2050 (FUT-P2050) have been studied and compared with FUT-P2010. Finally, the effects of a future mitigation scenario are quantified. That scenario includes the use of 80% of renewables sources to produce energy (REN80-P2010 and REN80-2050) and allows to isolate the effect of a future mitigation strategy based on energy production from renewable sources.

3.1 Levels of PM2.5 in present and future scenarios

Figure 4 shows the PM2.5 mean annual concentration over Europe for the present period (1991-2010) and the changes projected in the future scenario (2031-2050, RCP8.5) both with emissions from ACCMIP and in the mitigation scenario (2031-2050, REN80). As also stated in previous works (Tarín-Carrasco et al., 2019; Tarín-Carrasco et al., 2020), the chemistry/climate simulations revealed the presence of some areas in Europe exceeding the annual PM2.5 limit value (25 μg m^{-3}) established by the European Directive 2008/50/EC on ambient air quality and cleaner air for Europe. For the present period, eastern Europe and some large cities and conurbations have the highest concentrations of fine particles, with some cities cities as Paris (France), Krakow (Poland) or Moscow (Russia) presenting elevated levels and exceeding 25 μg m^{-3}.

The future changes in PM2.5 concentration attributable to GHG-induced climate change under the RCP8.5 scenario indicate a mean increase of 0.7 μg m^{-3}, with higher increases over southern of Europe. These results are in agreement with those of Silva et al. (2017) and Park et al. (2020), among others, who show an overall increase in surface PM2.5 concentration over most land regions. On the other hand, slight decreases are projected mainly over the Scandinavian countries and some Baltic areas (-0.2 μg m^{-3}). The increase of PM2.5 over this area under the mitigation scenario (REN80) can be > 0.5 μg m^{-3}. Although air quality improves overall in Europe; areas such as Paris, Krakow or Moscow will keep exceeding the European Directive threshold.

On the other hand, the REN80 scenario indicates an overall improvement of air pollution related to PM2.5 in Europe, especially over eastern Europe. In that area, the effect of the REN80 largely counteracts the climate penalty (reductions of >-1.0 μg m^{-3} with respect to present concentrations and >-1.4 μg m^{-3} as average changes with respect to RCP8.5 scenario, reaching -2.5 μg m^{-3} over certain hotspots). The reason for that decrease over Eastern Europe is the high ratio of fossil fuels in the energy mix of countries in that area (European Environment Agency, 2020). Again, those results are in agreement with
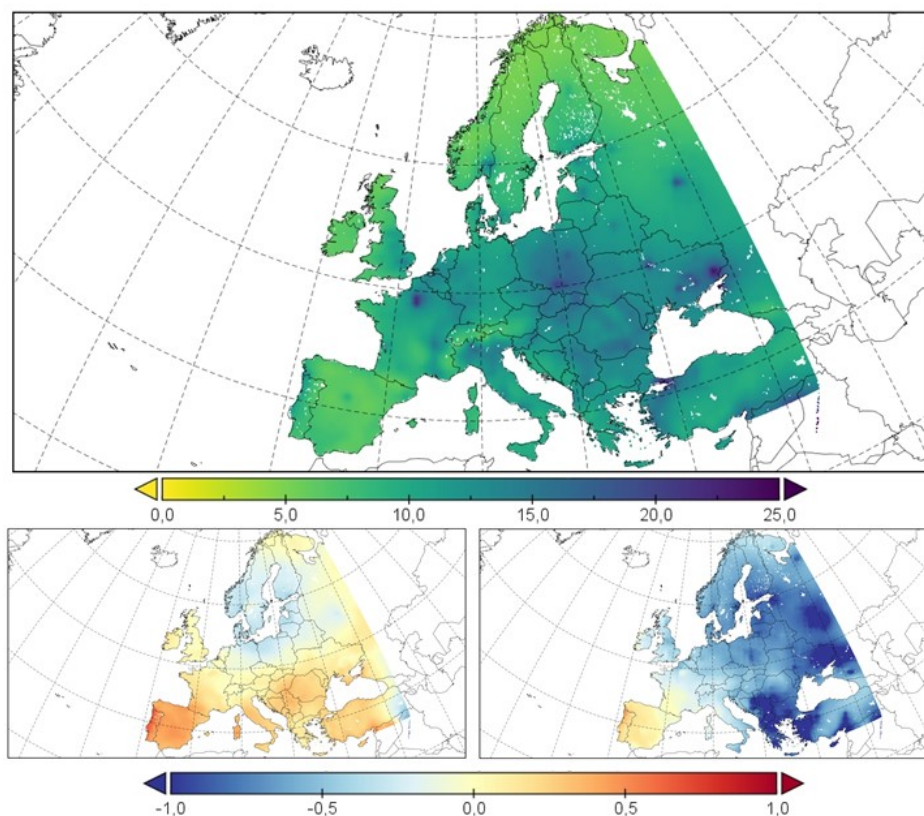
Figure 4. PM2.5 concentration over Europe for (top) present period (1991-2010); (bottom-left) difference with the future scenario (2031-2050, RCP8.5); and (bottom-right) difference with the future (2031-2050, RCP8.5)+80% renewables energies scenario (REN80). All units in μg m^{-3}.

previous works found in the scientific literature. For instance Liang et al. (2018) obtain a reduction of almost -0.9 μg m^{-3} for a future scenario with a reduction of 20% in anthropogenic emissions due to power and industry sources.

It is also noticeable that northern Europe will benefit both from the climate penalty and the mitigation scenarios. This benefit
205 cannot be observed over southern Europe, where the benefits of mitigation strategies might not compensate the effect caused by climate change on PM2.5 levels (fine particles will increase their concentrations in southern Europe as a consequence of decreasing precipitations and increased emissions from natural sources in this target area) (Jiménez-Guerrero et al., 2013b) (Figure 4).

3.2 Estimation of present premature deaths over Europe (PRE-P2010)

210 Figure 5 depicts the annual excess PD associated with present PM2.5 pollution (PRE-P2010). For the present period (1991-2010), 895,000 (95% CI 725,000-1,056,000) annual PD are estimated over the European area, in agreement with the results

of Andersson et al. (2009) and Crippa et al. (2019). The highest incidence of excess PD are estimated for Eastern Europe (467,000 annual PD, 95% CI 378,200-551,100) (Table 4), while the highest incidence of normalized PD per 100,000 adult inhabitants are found over Central Europe (229.4 PD/100,000 habitats per year). This latter result is in agreement with results

215 by Silva et al. (2016a), who identify the Benelux as the European region with the highest excess mortality rates associated to air pollution.
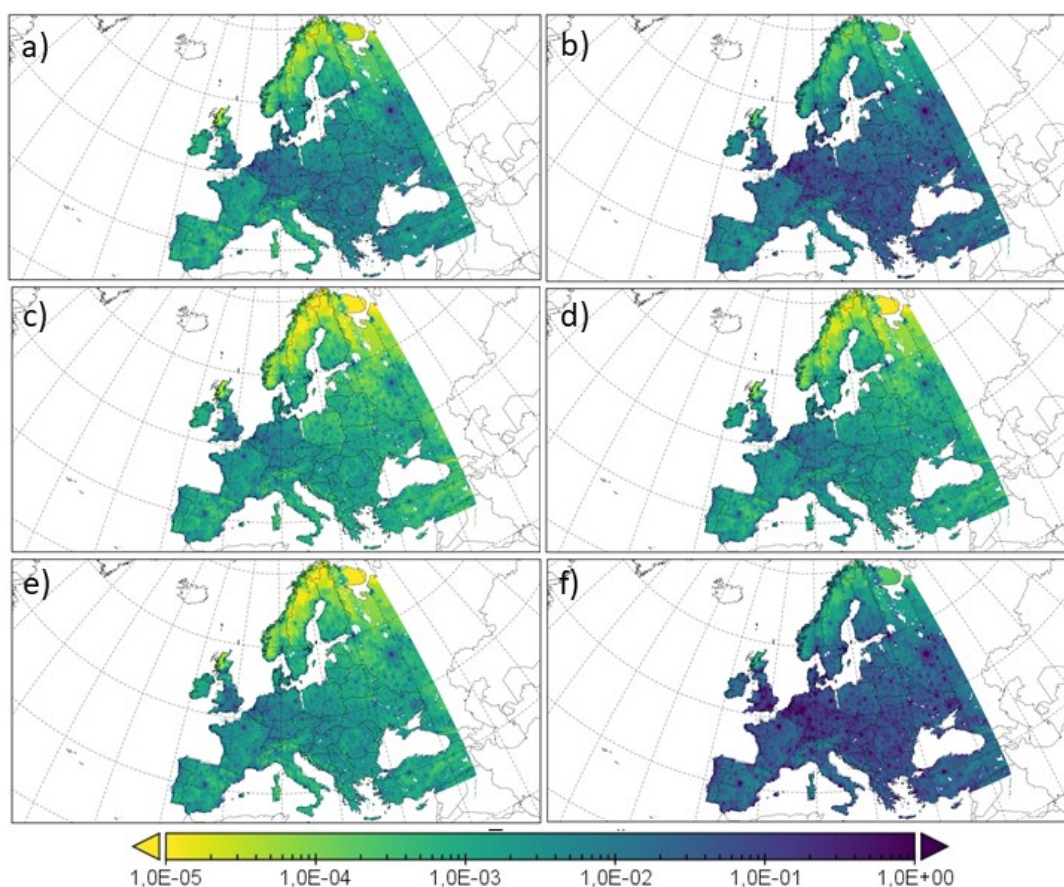
Figure 5. Estimation of PD over Europe for the PRE-P2010 case for different endpoints: (a) CEV, (b) IHD, (c) COPD, (d) LC, (e) LRI and (f) all. All units are PD/km^2 per year.

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When considering individual endpoints (Figure 6), the main cause of excess PD associated to PM2.5 in the European domain is related to cardiovascular diseases (IHD+CEV), especially over Eastern Europe. Moreover, CEV and IHD are those causes of PD with the highest differences between each target area. The PD incidence over Eastern Europe is caused mainly by

220 IHD+CEV, totalizing > 60% of the premature mortality burden in Europe (Figure 6) because of (1) the higher population (51% of the total European population contemplated in this contribution) in comparison with Central (19% of European population)

Table 4. Estimated incidence of excess premature deaths (PD, in thousands) and PD per 100,000 habitants for each European region in all scenarios covered. Numbers in parenthesis represent the 95% confidence interval.

	Present	PRE-P2010	RCP8.5	FUT-P2010	RCP8.5	REN80-P2010	RCP8.5	FUT-P2050	RCP8.5	REN80-P2050
	PD × 10³	PD/100,000 h.	PD × 10³	PD/100,000 h.	PD × 10³	PD/100,000 h.	PD × 10³	PD/100,000 h.	PD × 10³	PD/100,000 h.
Western EU	174.9	98.0	177.2	99.3	172.4	96.5	327.2	168.5	318.2	163.8
	(141.7-206.4)	(79.4-115.6)	(143.5-209.1)	(80.4-117.2)	(139.6-203.4)	(78.2-113.9)	(265.0-386.1)	(136.5-198.8)	(257.7-375.5)	(132.7-193.3)
Central EU	252.7	229.4	250.7	227.6	244.3	221.8	448.3	372.5	437.5	363.6
	(204.7-298.2)	(185.8-270.7)	(203.1-295.8)	(184.4-268.6)	(197.9-288.3)	(179.7-261.7)	(363.0-528.9)	(301.7-439.6)	(354.4-516.3)	(294.5-429.0)
Eastern EU	466.7	167.3	467.9	167.7	444.8	159.5	759.9	262.0	723.6	249.4
	(378.0-550.7)	(135.5-197.4)	(379.0-552.1)	(135.8-197.9)	(360.3-524.9)	(129.2-188.2)	(615.5-896.7)	(212.2-309.2)	(586.1-853.8)	(202.0-294.3)
EUROPE	894.3	167.5	895.8	157.8	861.5	151.8	1,535.4	253.9	1,479.3	244.7
	(724.4-1,055.3)	(135.7-197.7)	(725.6-1,057.0)	(127.8-186.2)	(697.8-1,016.6)	(123.0-179.1)	(1,243.7-1,811.8)	(205.7-299.6)	(1,212.8-1,766.8)	(198.2-288.7)

(PRE-P2010): PD for the present case; (FUT-P2010): PD for the future scenario with population at 2010 levels; (REN80-P2010): PD for the future mitigation scenario with population at 2010 levels; (FUT-P2050): PD for the future scenario with population projections of UN for 2050; (REN80-P2010): PD for the future mitigation scenario with population at 2010 levels; (REN80-P2050): PD for the future mitigation scenario with population projections of UN for 2050.

and Western Europe (30% of the European habitants); and (2) the higher PM2.5 concentrations (as previously shown in Figure 4). Those results are analogous for the total PD by all causes: PD are similar (with respect to their percentage) to the population held in the respective areas. In this sense, Eastern Europe represents more than 50% of mortality in Europe, while Central and 225 Western Europe add around 20 and 30% of PD, proportional to their population.
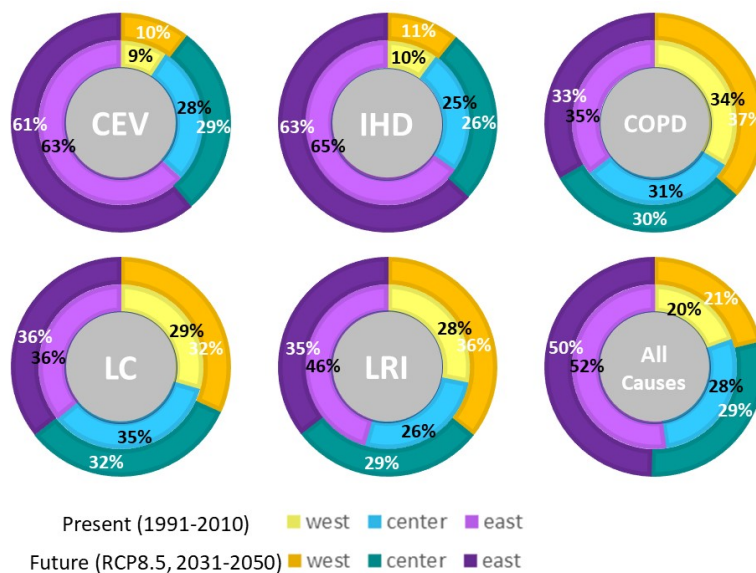
Figure 6. Relative contribution of each cause of PD by European region for the PRE-P2010 and the FUT-P2050.

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It is noticeable that for COPD, LRI and LC, the three studied regions contribute with a similar percentage to total PD over Europe (around 30%), which is indicative that the COPD, LRI and LC ratios are much higher over Western Europe (30% of European population) and Central Europe (19% of total European population) than over Eastern Europe (51% of population).

3.3 Isolating the climate penalty effect over premature deaths over Europe (FUT-P2010)

230 In this Section the role of the climate penalty is assessed by comparing two simulations differing only in the radiative forcing (1991-2010 vs. RCP8.5 2031-2050) (hence the two model runs FUT-P2010 vs. PRE-2010). For that, population has been kept constant at 2010 levels. The results presented in Table 5 indicate that the climate penalty has a very limited impact on air pollution-related future premature deaths over Europe (Figure 7). When comparing the total incidence of PD in the PRE-P2010 and FUT-P2010 cases, only a +0.2% increase is projected in the future scenario. However, this increase is uneven

235 among different regions of Europe. While total PD per 100,000 adults (Table 4) increase in Western Europe by nearly 2% and in Eastern Europe by 0.2%, the mortality decreases by -0.8% over Central Europe. These variations in the distribution of PM2.5 in Europe, considering a future RCP8.5 scenario, is mainly due to changes in precipitation. The decrease in rainfall in southern Europe (e.g. Jiménez-Guerrero et al. (2012); Domínguez-Morueco et al. (2019)) and the increase in rainfall in northern and central Europe projected for this scenario (e.g. Jiménez-Guerrero et al. (2013b); Jacob et al. (2018)) affect the wet scavenging

240 of particles, the fundamental process for the removal of particles from the atmosphere (e.g. Ohata et al. (2016); de Bruine et al. (2018); Hou et al. (2018)).

Table 5. Estimated annual premature deaths (PD $\times 10^3$) associated to fine particules for total population in all scenarios covered (in thousands).

	Present	PRE-P2010	RCP8.5	FUT-P2010	RCP8.5	REN80-P2010	RCP8.5	FUT-P2050	RCP8.5	REN80-P2050
	PD $\times 10^3$	PD/100,000 h.	PD $\times 10^3$	PD/100,000 h.	PD $\times 10^3$	PD/100,000 h.	PD $\times 10^3$	PD/100,000 h.	PD $\times 10^3$	PD/100,000 h.
COPD	27.7	4.9	27.8	4.9	26.5	4.7	52.2	8.6	49.8	8.2
	(22.4-32.7)	(4.0-5.8)	(22.5-32.8)	(4.0-5.8)	(21.5-31.3)	(3.8-5.5)	(42.3-61.6)	(7.0-10.1)	(40.3-58.8)	(6.6-9.7)
LC	47.6	74.7	47.7	74.8	45.4	71.8	68.7	121.7	65.3	116.8
	(40.0-54.7)	(62.7-85.9)	(40.1-54.9)	(62.8-86.0)	(38.1-52.2)	(60.3-82.6)	(57.7-79.0)	(102.1-139.8)	(54.9-75.1)	(98.1-134.3)
LRI	42.4	8.4	42.6	8.4	40.0	8.0	71.1	11.4	67.0	10.8
	(35.6-48.8)	(7.1-9.7)	(35.8-49.0)	(7.1-9.7)	(33.6-46.0)	(6.7-9.2)	(59.7-81.8)	(9.6-13.1)	(56.3-77.1)	(9.1-12.4)
CEV	86.9	15.3	87.1	15.3	81.8	14.4	151.6	25.1	142.4	23.5
	(73.0-99.9)	(12.9-17.6)	(73.2-100.2)	(12.9-17.6)	(68.7-94.1)	(12.1-16.6)	(127.3-174.3)	(21.1-28.9)	(119.6-163.8)	(19.7-27.0)
IHD	424.1	7.5	424.5	7.5	407.5	7.0	736.0	11.8	706.3	11.1
	(356.2-487.7)	(6.3-8.6)	(356.5-488.1)	(6.3-8.6)	(342.3-468.6)	(5.9-8.1)	(618.2-846.4)	(9.9-13.6)	(593.3-812.2)	(9.3-12.8)
Other NCD	265.6	46.8	266.2	46.9	260.3	45.9	455.8	75.8	448.5	74.2
	(140.8-329.3)	(24.8-58.0)	(141.1-330.1)	(24.9-58.2)	(138.0-322.8)	(24.3-56.9)	(241.6-565.2)	(40.2-94.0)	(237.7-556.1)	(39.3-92.0)
All endpoints	894.3	167.5	895.8	157.8	861.5	151.8	1,535.4	253.9	1,479.3	244.7
	(724.4-1,055.3)	(135.7-197.7)	(725.6-1,057.0)	(127.8-186.2)	(697.8-1,016.6)	(123.0-179.1)	(1,243.7-1,811.8)	(205.7-299.6)	(1,212.4-1,766.8)	(198.2-288.7)

(PRE-P2010): PD for the present case; (FUT-P2010): PD for the future scenario with population at 2010 levels; (REN80-P2010): PD for the future mitigation scenario with population at 2010 levels; (FUT-P2050): PD for the future scenario with population projections of UN for 2050; (REN80-P2010): PD for the future mitigation scenario with population at 2010 levels; (REN80-P2050): PD for the future mitigation scenario with population projections of UN for 2050.

It should be highlighted that the cause of premature mortality most sensitive to changes in PM2.5 is CEV+IHD (Figure 7), as also found by previous studies (Pope et al., 2009, 2020). The spatial patterns of change of this latter endpoint condition the patterns of total variation of PD by all causes. IHD mortality rates increase by nearly 3% from 424,000 (95% CI 356,100-

245   487,600) to 425,000 (95% CI 357,000-488,800) in the FUT-P2010 case. On the other hand, COPD, LC, LRI and Other NCD
barely change, since these causes are not too much sensitive to PM2.5 concentration as IHD, as discussed in Tarín-Carrasco
et al. (2020).
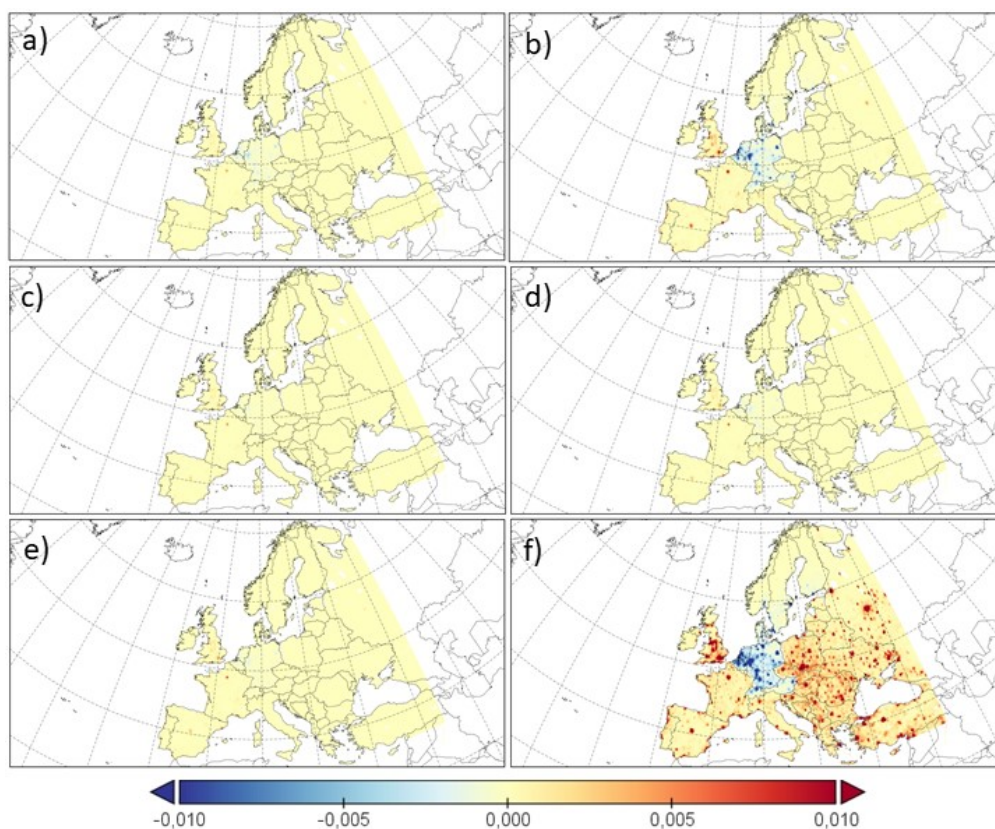
Figure 7. Differences between PD over Europe for the FUT-PRE2010 and the PRE-P2010 case for different endpoints: (a) CEV, (b) IHD,
(c) COPD, (d) LC, (e) LRI and (f) all endpoints. All units are PD/km^2.

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3.4   Estimation of future premature deaths over Europe with a projected population (FUT-P2050)

The previous Section analyzed the contribution of climate change alone (RCP8.5 scenario, keeping population constant) to
250   PD over Europe. Here, the impact of projected changes in the population following UN2050 data is added to climate penalty.
This scenario is denoted as FUT-P2050. As shown in Figure 8 the highest mortality incidence in FUT-P2050 is related to
IHD, which has an overspread spatial pattern in the target domain. For FUT-P2050, the projected PD incidence increases to
1,540,000 (95% CI 1,247,000-1,818,000), with Eastern Europe being the most affected region, with almost half of the excess
mortality rate over Europe (Table 4).

255   The premature mortality burdens associated with exposure to ambient PM2.5 in Europe are expected to increase by 72% in
the year 2050 when comparing the PRE-P2010 and FUT-P2050 simulations, from 894,000 (95% CI 723,900-1,055,400) PD
per year in 1990-2010 to 1,540,000 (95% CI 1,247,000-1,818,000) PD per year in 2031-2050 (Table 5). The leading cause
of PM2.5-related mortality is IHD for both present and future cases: 424,000 (95% CI 356,200-487,800) PD per year, which
increases by 74%, to 736,000 (95% CI 618,200-846,400) PD per year in the FUT-P2050 case. IHD is followed by Other-NCD,
260   with 265,600 (95% CI 140,800-329,300) PD per year increasing by 73%, to 458,400 (95% CI 243,000-568,400) PD per year
in the FUT-P2050 case.
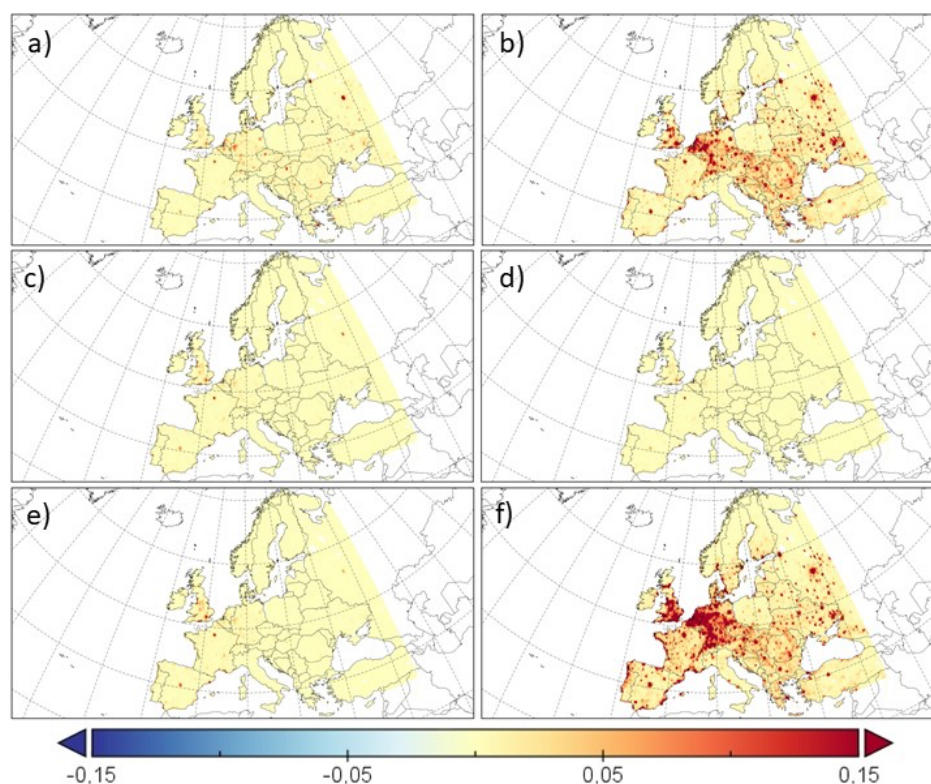
Figure 8. Differences in future premature mortality for the future scenario considering the population dynamics for 2050 (FUT-P2050).
Endpoints considered are (a) CEV, (b) IHD, (c) COPD, (d) LC, (e) LRI and (f) All endpoints. All units in PD/km^2.

When assessing the relative contribution of each endpoint to the total PD burden both in PRE-P2010 and FUT-P2050,
Figure 6 indicates that future climate change and the modification of population by the year 2050 will barely change the
relative percentage of each mortality cause by region, so discussion is analogous to that presented in Section 3.2. The only
265   exception is for LRI, which experiences several important changes between PRE-P2010 and FUT-P2050 (increasing from a
28% contribution in Western Europe for the present to 36% over this same area in the FUT-P2050 case; and from 35% in
PRE-P2010 over Eastern Europa to 46% in FUT-P2050 over this same domain).

3.5 Effect of the future mitigation scenario (REN80-P2010 and REN80-P2050)

This case takes into account the climate change action (RCP8.5, 2031-2050) together with the emission scenario where it
270 is assumed that 80% energy production over Europe is provided by renewables sources (REN80). For the analysis of this
impact, a scenario where the population has been kept constant at 2010 levels (REN80-P2010) and a second scenario where
the population dynamics has been taken into account (REN80-P2050) is analyzed below.

Figure 9 shows that in REN80-P2010 the PD incidence will be lower than in the REN80-P2050 scenario, which considers
changes in the population, as previously discussed for the FUT-P2010 and FUT-2050. Large central-Europe cities are the areas
275 where the PD incidence will increase most with a changing population (increases in the density and age of population, as
previously shown in Figure 1). A summary of the excess mortality incidence in all scenarios is presented in Table 4.

The incidence of all the mortality causes studied decreases in the future mitigation scenarios (REN80-P2010 and REN80-
P2050) when compared to the corresponding FUT-P2010 and FUT-2050 simulations, respectively, by 4%. This decrease is
especially found in central and eastern regions regarding the number of total PD (Table 4). This is explained by the fact that an
280 important part of the anthropogenic emissions of PM2.5 over Europe is associated to power generation (Crippa et al., 2019).
Precisely, this contribution is 15.1% here. Table 5 indicates that CEV and IHD present the largest relative reductions of the
incidence ratio of PD in the REN80-P2050 scenario with respect to FUT-P2050 (-6% changes in annual PD). COPD and
LRI show a -5% change between both scenarios, Figure 10), with around -4% cases less for the renewable scenario for LC.
Other NCD decreases by -2% in the REN80 simulations. Other NCD and CEV are the endpoints experiencing the largest
285 improvement in the mitigation scenario, with a decrease in annual excess PD of 30,000 (95% CI 15,900 - 37,200) and 10,000
(95% CI 5,300 - 12,400), respectively.

3.5.1 Effect of the projected population for 2050

Last, this section tries to shed some light on the effect of the changes in the population projected (mainly, the aging of the
European population, since almost half all the PD over Europe occurs in the age group of 80+). A comparison of the mortality
290 burden for each age group considered among the different future scenarios is shown in the Supplementary Material (Table
SM2).

In particular, the effect of the aging of population is clearly noticeable when comparing the FUT-P2010 and the FUT-P2050
scenarios, differing only in the population taking as basis for the estimation of PD over Europe. While the number of PD
decreases in FUT-P2050 for younger age ranges, it generally increases for people over 65 years. For instance, the number of
295 PD per 100,000 habitants in the 65-69 age range increases from 237 to 248 deaths/100,000 habitants; and the same statistics
moves from 1037 to 1044 in the 80+ age range. This fact could be ascribed to the increase in the number of population falling
within this group in the UN 2050 projection (Figure 1). Conversely, for younger age ranges, mortality will decrease in the
future as population does. For instance, the 30-34 age range moves from 14 PD/100,000 habitants in the FUT-P2010 case to 13
PD/100,000 habitants in FUT-P2050. Overall, the total number of premature deaths will increase from 158 to 254 PD/100,000
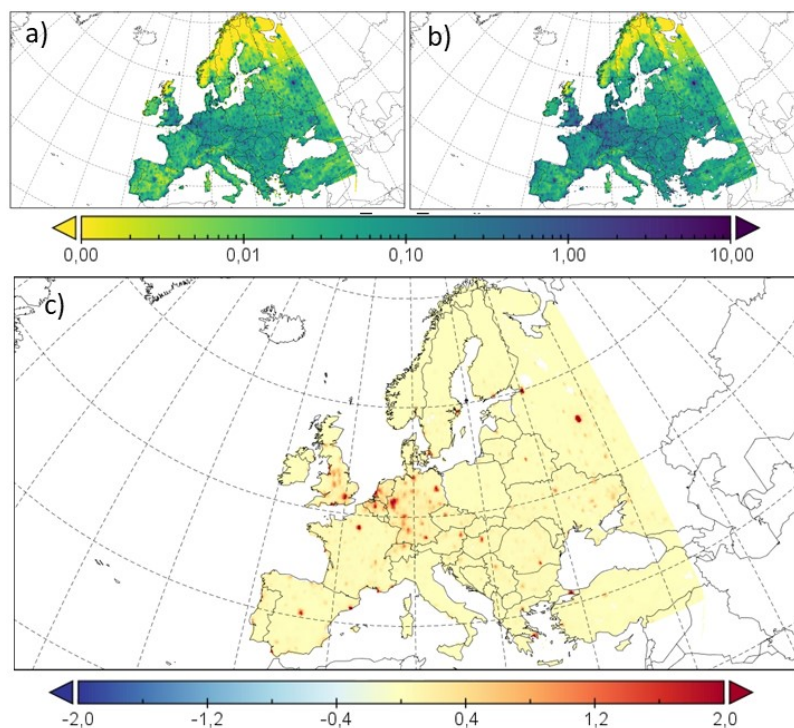
Figure 9. Future (2031-2050) premature deaths for (a) the mitigation scenario keeping constant the present population (REN80-P2010) and (b) mitigation scenario considering the population projections for 2050 (REN80-P2050). (c) Differences between both future scenarios (REN80-P2050 minus REN80-P2010). All units in PD/km^2.

300 (+61%) as a consequence of the aging of the population, despite a global decrease of -0.2% in total population over Europe is projected by the UN for the year 2050.

With respect to individual endpoints, the PD incidence caused by LRI keeps a similar ratio until the group 80+, when the incidence increases considerably (Figure 11). Hence, LRI is not strongly sensitive to the aging of population, but to the modifications in the number of dwellers. LRI increases from 42,000 (95% CI 35,200-48,300) in PRE-P2010 to 71,000 (95%
305 CI 59,500-81,700) PD per year in the FUT-P2050 case. Also, LC results are to be highlighted (48,000 PD per year, 95% CI 40,300-55,200 in PRE-P2010 vs. 69,000 PD per year, 95% CI 57,900-79,400; associated to PM2.5 air pollution in the FUT-P2050 case). For this cause, the number of deaths increases with the age up to a maximum for the age range 70-74. From there, the number of deaths decreases again. This fact could be ascribed to the fact that the impacts of lung cancer in mortality is not immediate, as in other endpoints covered such as IHD or CEV. Henceforth, people affected by lung cancer at such advanced
310 age may die from another cause instead of LC. Finally, it is also noteworthy that PD in adults (25 until 60 years) decreases in the FUT-P2050 case for all the mortality causes studied. From 60 years and elder, PD increase in comparison with the present period due to the aging of the population in the future. For this reason, a higher incidence is estimated for aged people.
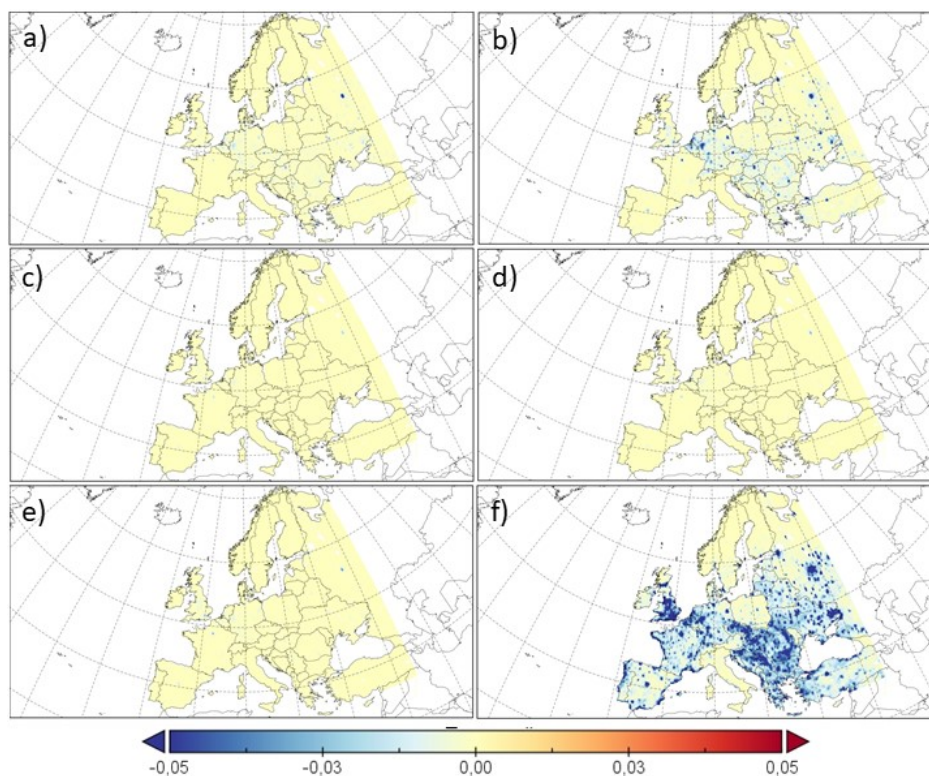
Figure 10. Differences in future premature mortality for the future scenario P2050 and the mitigation scenario (REN80-P2050), both considering the population projections for 2050. Endpoints considered are (a) CEV, (b) IHD, (c) COPD, (d) LC, (e) LRI and (f) All endpoints. All units in Premature Deaths (PD) per km^2.

Hence, the differences between PRE-P2010 and FUT-P2010/P2050 must be sought in the differences among the risk ratios estimated by Equation 2. RRs are higher for younger age groups, with the incidence of PD higher for older groups. The baseline values (y_0) in Equation 2 are much higher for advanced ages, since elder people presents higher baseline mortality rates than younger dwellers.

4 Summary and Conclusions

This contribution has estimated the incidence of excess premature mortality associated to fine particulate matter for different present and future scenarios. The non-linear methodology employed depicted 894,000 (95% CI 723,900-1,055,400) annual premature deaths (PD) over Europe during the 1991-2010 period. The most important conclusions can be summarized as:

1. Effect of climate penalty: when the effect of climate penalty under the RCP8.5 scenario is isolated, the total premature mortality could be increased by around 2,000 PD (+0.2% in the FUT-P2010 vs. PRE-P2010 case), increasing from 894,000 (95% CI 723,900-1,055,400) to 896,000 (95% CI 725,500-1,057,800) over the target domain of Europe. Hence-
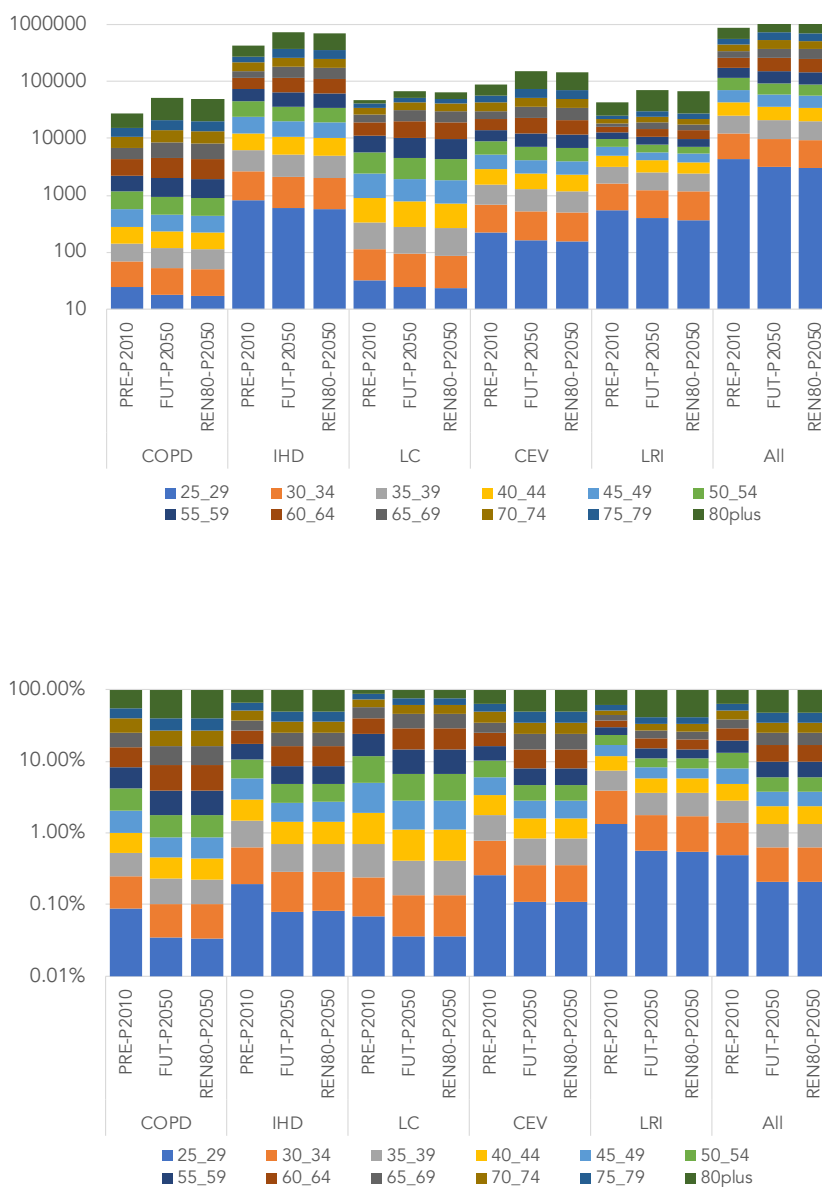
Figure 11. Present (PRE-P2010) and future (FUT-P2010/P2050) estimation of PD per pathology and age group over Europe (top, Total PD per year; bottom, %).

forth, the effect of climate penalty is limited due to the compensating effects of increased mortality over Western (+1.3
PD/100,000 h.) and Eastern Europe (+0.4 PD/100,000 h.), but a decrease over Central Europe (-2.2 PD/100,000 h.)
(Figure 12) as a consequence of the reduced PM2.5 levels over this latter region under the RCP8.5 due to increased
precipitation. In this sense, the domain of Central Europe (that includes northern and central areas of the continent)
will benefit from the climatic effects, while the climate penalty will have an important effect in the domain of Western
Europe, that includes southwestern European areas, where the concentrations of PM2.5 are projected to increase in the
RCP8.5 scenario.
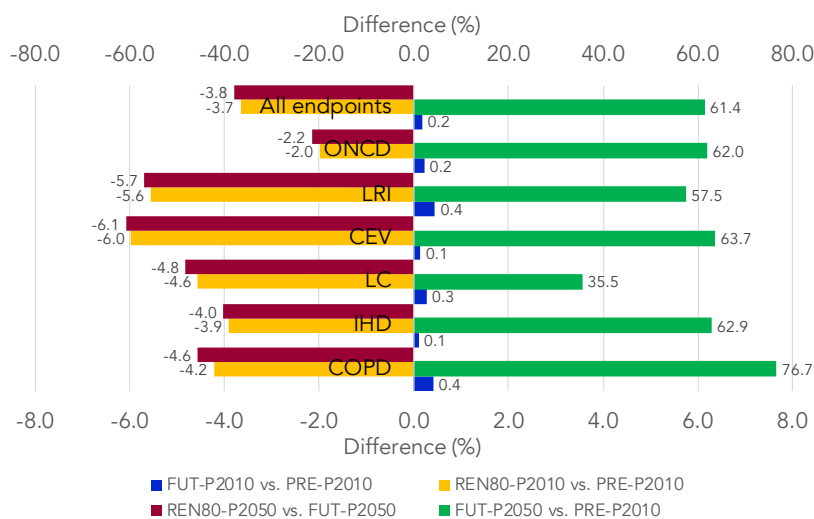
Figure 12. Relative differences for PD/100,000 habitants between the different scenarios for all the endpoints included in this work. FUT-P2010, FUT-P2050 and REN80-P2010 have been compared to the PRE-P2010 scenario, while the differences of the REN80-P2050 scenarios are estimated with respect to the FUT-P2050 scenario.

2. Impact of changes in the projected population: this modification, together with the climate penalty (FUT-P2050), leads to an excess premature mortality rate of 1,540,000 (95% CI 1,247,000-1,818,000), that is, an increase of 71.96% with respect to the present scenario and 71.67% to the future scenario in which only the climate penalty is considered. In contrast to the scenario in which population is kept constant (FUT-P2010), PD in central Europe in the future will increase because of the increase in the number of elderly population.

3. Impact of mitigation scenarios: The introduction of energy policies favoring renewable energies (80% of energy generated from renewable sources) could lead to a decrease of 60,000 (95% CI 48,600-70,900) annual PD in the year 2050 (1,480,000 PD per year, 95% CI 1,198,400-1,747,000, in the REN80-P2050 case, a decrease of -4%) in comparison with

the FUT-P2050 case). So, mortality will importantly increase in the future scenario, but trusting in renewable energy
340   policies could reduce the number of PD, being easter Europe the most benefited area.

4. Causes of premature mortality: With respect to the different endpoints, IHD is the most important cause of mortality over
   Europe (over 50% of total premature mortality), with $\sim$ 424,000 (95% CI 356,200-487,800) annual PD in the present
   and the climate penalty scenario. When the change in 2050 population is considered, 736,000 (95% CI 618,200-846,400)
   annual PD are associated to this endpoint. This number reduces by 30,000 (95% CI 15,900 - 37,200) annual PD when
345   the mitigation by renewables energy is considered. This results are caused by the high sensitivity of IHD to PM2.5. The
   second most important cause is CEV, with a $\sim$ 10% contribution to the total premature mortality. LRI, LC and COPD
   represent a 5%, 4% and 3%, respectively, of the total premature mortality. Last, it should be highlighted that other NCD
   causes represents a 30% of the PD in Europe.

This study presents an added value with respect to previous contributions. For instance, different baseline information has
350   been included depending on the area of Europe considered. In addition, the PD incidence by age-range has been detailed here,
highlighting the increase in future mortality not only by climate penalty, but because of an aged European population projected
for the year 2050. The aging of the population will increase the number of sensitive dwellers and thus, the PD burden over the
European domain.

Last, it is important to bear in mind that these results are estimated for different future cases and scenarios. Henceforth,
355   these estimations are associated to different variables that are sometimes difficult to project, such as the death rate; the levels
of air pollution (which depend on emission scenarios and the human influence on emissions like traffic, power generation
or agriculture); and the demographic trends (elderly population, urbanization processes). Some of these variables are hard to
control, but despite the uncertainties it becomes clear from this contribution that governments and public entities must take
project and clearly implement mitigation policies, which could improve air quality and therefore, the wellness of the European
360   citizens.

Data availability. The data is available upon contacting the corresponding author (pedro.jimenezguerrero@um.es)

Author contributions. PT-C wrote the manuscript, with contributions from PJ-G. LP-P and PJ-G designed the air quality/climate experiments; P-TC conducted the numerical estimations of premature mortality, with the support of UI, PJ-G and CG. P-TC did the analysis, with the support of UI, CG, LP-P and PJ-G.

365   *Competing interests.* The authors declare no conflict of interest.

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References

Andersson, C., Bergstrom, R., and Johansson, C.: Population exposure and mortality due to regional background PM in Europe – Long-term simulations of source region and shipping contributions, Atmospheric Environment, 43, 3614 – 3620, https://doi.org/10.1016/j.atmosenv.2009.03.040, 2009.

Anenberg, S. C., West, J. J., Yu, H., Chin, M., Schulz, M., Bergmann, D., Bey, I., Bian, H., Diehl, T., Fiore, A., Hess, P., Marmer, E., Montanaro, V., Park, R., Shindell, D., Takemura, T., and Dentener, F.: Impacts of intercontinental transport of anthropogenic fine particulate matter on human mortality, Air Quality, Atmosphere & Health, 7, 369–379, https://doi.org/10.1007/s11869-014-0248-9, 2014.

Balakrishnan, K., Dey, S., Gupta, T., Dhaliwal, R. S., Brauer, M., Cohen, A. J., Stanaway, J. D., Beig, G., Joshi, T. K., Aggarwal, A. N., Sabde, Y., Sadhu, H., Frostad, J., Causey, K., Godwin, W., Shukla, D. K., Kumar, G. A., Varghese, C. M., Muraleedharan, P., Agrawal, A., Anjana, R. M., Bhansali, A., Bhardwaj, D., Burkart, K., Cercy, K., Chakma, J. K., Chowdhury, S., Christopher, D. J., Dutta, E., Furtado, M., Ghosh, S., Ghoshal, A. G., Glenn, S. D., Guleria, R., Gupta, R., Jeemon, P., Kant, R., Kant, S., Kaur, T., Koul, P. A., Krish, V., Krishna, B., Larson, S. L., Madhipatla, K., Mahesh, P. A., Mohan, V., Mukhopadhyay, S., Mutreja, P., Naik, N., Nair, S., Nguyen, G., Odell, C. M., Pandian, J. D., Prabhakaran, D., Prabhakaran, P., Roy, A., Salvi, S., Sambandam, S., Saraf, D., Sharma, M., Shrivastava, A., Singh, V., Tandon, N., Thomas, N. J., Torre, A., Xavier, D., Yadav, G., Singh, S., Shekhar, C., Vos, T., Dandona, R., Reddy, K. S., Lim, S. S., Murray, C. J. L., Venkatesh, S., and Dandona, L.: The impact of air pollution on deaths, disease burden, and life expectancy across the states of India: the Global Burden of Disease Study 2017, The Lancet Planetary Health, 3, e26–e39, https://doi.org/10.1016/S2542-5196(18)30261-4, 2019.

Brook, R. D., Rajagopalan, S., Pope, C. A., Brook, J. R., Bhatnagar, A., Diez-Roux, A. V., Holguin, F., Hong, Y., Luepker, R. V., Mittleman, M. A., Peters, A., Siscovick, D., Smith, S. C., Whitsel, L., and Kaufman, J. D.: Particulate Matter Air Pollution and Cardiovascular Disease, Circulation, 121, 2331–2378, https://doi.org/10.1161/CIR.0b013e3181dbece1, 2010.

Burnett, R., Chen, H., Szyszkowicz, M., Fann, N., Hubbell, B., Pope, C. A., Apte, J. S., Brauer, M., Cohen, A., Weichenthal, S., Coggins, J., Di, Q., Brunekreef, B., Frostad, J., Lim, S. S., Kan, H., Walker, K. D., Thurston, G. D., Hayes, R. B., Lim, C. C., Turner, M. C., Jerrett, M., Krewski, D., Gapstur, S. M., Diver, W. R., Ostro, B., Goldberg, D., Crouse, D. L., Martin, R. V., Peters, P., Pinault, L., Tjepkema, M., van Donkelaar, A., Villeneuve, P. J., Miller, A. B., Yin, P., Zhou, M., Wang, L., Janssen, N. A. H., Marra, M., Atkinson, R. W., Tsang, H., Quoc Thach, T., Cannon, J. B., Allen, R. T., Hart, J. E., Laden, F., Cesaroni, G., Forastiere, F., Weinmayr, G., Jaensch, A., Nagel, G., Concin, H., and Spadaro, J. V.: Global estimates of mortality associated with long-term exposure to outdoor fine particulate matter, Proceedings of the National Academy of Sciences, 115, 9592–9597, https://doi.org/10.1073/pnas.1803222115, 2018.

Cohen, A. J., Brauer, M., Burnett, R., Anderson, H. R., Frostad, J., Estep, K., Balakrishnan, K., Brunekreef, B., Dandona, L., Dandona, R., Feigin, V., Freedman, G., Hubbell, B., Jobling, A., Kan, H., Knibbs, L., Liu, Y., Martin, R., Morawska, L., Pope, C. A., Shin, H., Straif, K., Shaddick, G., Thomas, M., van Dingenen, R., van Donkelaar, A., Vos, T., Murray, C. J. L., and Forouzanfar, M. H.: Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015., Lancet (London, England), 389, 1907–1918, https://doi.org/10.1016/S0140-6736(17)30505-6, 2017.

Crippa, M., Janssens-Maenhout, G., Guizzardi, D., Van Dingenen, R., and Dentener, F.: Contribution and uncertainty of sectorial and regional emissions to regional and global $PM_{2.5}$ health impacts, Atmospheric Chemistry and Physics, 19, 5165–5186, https://doi.org/10.5194/acp-19-5165-2019, 2019.

de Bruine, M., Krol, M., van Noije, T., Le Sager, P., and Röckmann, T.: The impact of precipitation evaporation on the atmospheric aerosol distribution in EC-Earth v3.2.0, Geoscientific Model Development, 11, 1443–1465, https://doi.org/10.5194/gmd-11-1443-2018, https://gmd.copernicus.org/articles/11/1443/2018/, 2018.

Domínguez-Morueco, N., Ratola, N., Sierra, J., Nadal, M., and Jiménez-Guerrero, P.: Combining monitoring and modelling approaches for BaP characterization over a petrochemical area, Science of The Total Environment, 658, 424 – 438, https://doi.org/10.1016/j.scitotenv.2018.12.202, 2019.

European Climate Foundation: Roadmap 2050: a practical guide to a prosperous, low-carbon Europe. Volume I. Technical and economic assessment, www.roadmap2050.eu/project/roadmap-2050, 2010.

European Environment Agency: EMEP/EEA air pollutant emission Inventory Guidebook. Technical guidance to prepare national emission inventories. EEA Report No 13/2019, https://doi.org/10.2800/293657, https://www.eea.europa.eu/publications/emep-eea-guidebook-2019, 2019.

European Environment Agency: Indicator assessment: Overview of electricity production and use in Europe, https://www.eea.europa.eu/data-and-maps/indicators/overview-of-the-electricity-production-2/assessment-4, 2020.

Evans, J., van Donkelaar, A., Martin, R. V., Burnett, R., Rainham, D. G., Birkett, N. J., and Krewski, D.: Estimates of global mortality attributable to particulate air pollution using satellite imagery, Environmental Research, 120, 33 – 42, https://doi.org/https://doi.org/10.1016/j.envres.2012.08.005, 2013.

Fang, Y., Naik, V., Horowitz, L. W., and Mauzerall, D. L.: Air pollution and associated human mortality: the role of air pollutant emissions, climate change and methane concentration increases from the preindustrial period to present, Atmospheric Chemistry and Physics, 13, 1377–1394, https://doi.org/10.5194/acp-13-1377-2013, 2013.

Fang, Y., Mauzerall, D. L., Liu, J., Fiore, A. M., and Horowitz, L. W.: Impacts of 21st century climate change on global air pollution-related premature mortality, Climatic Change, 121, 239–253, https://doi.org/10.1007/s10584-013-0847-8, 2013a.

Ford, B. and Heald, C. L.: Exploring the uncertainty associated with satellite-based estimates of premature mortality due to exposure to fine particulate matter, Atmospheric Chemistry and Physics, 16, 3499–3523, https://doi.org/10.5194/acp-16-3499-2016, 2016.

Geels, C., Andersson, C., Hänninen, O., Lansø, A., Schwarze, P., Skjøth, C., and Brandt, J.: Future Premature Mortality Due to O3, Secondary Inorganic Aerosols and Primary PM in Europe ? Sensitivity to Changes in Climate, Anthropogenic Emissions, Population and Building Stock, International Journal of Environmental Research and Public Health, 12, 2837–2869, https://doi.org/10.3390/ijerph120302837, http://www.mdpi.com/1660-4601/12/3/2837, 2015.

Giorgetta, M., Jungclaus, J., Reick, C., Legutke, S., Brovkin, V., Crueger, T., Esch, M., Fieg, K., Glushak, K., Gayler, V., Haak, H., Hollweg, H.-D., Kinne, S., Kornblueh, L., Matei, D., Mauritsen, T., Mikolajewicz, U., Muller, U., Notz, D., Raddatz, T., Rast, S., Reckner, E., Salzmann, M., Schmidt, H., Schunur, R., Segschneider, J., Six, K., Stockhause, M., Wegner, J., Widmann, H., Wieners, K.-H., Claussen, M., Marotzke, J., and Stevens, B.: Forcing data for Regional Climate Models based on the MPI-ESM-LR model of the Max Planck Institute for Meteorology (MPI-M): The CMIP5 historical experiment., World Data Center for Climate (WDCC) at DKRZ, https://doi.org/10.1594/WDCC/RCM_CMIP5_historical-LR, 2012a.

Giorgetta, M., Jungclaus, J., Reick, C., Legutke, S., Brovkin, V., Crueger, T., Esch, M., Fieg, K., Glushak, K., Gayler, V., Haak, H., Hollweg, H.-D., Kinne, S., Kornblueh, L., Matei, D., Mauritsen, T., Mikolajewicz, U., Muller, U., Notz, D., Raddatz, T., Rast, S., Roeckner, E., Salzmann, M., Schmidt, H., Schunur, R., Segschneider, J., Six, K., Stockhause, M., Wegner, J., Widmann, H., Wieners, K.-H., Claussen, M., Marotzke, J., and Stevens, B.: Forcing data for Regional Climate Models based on the MPI-ESM-LR model of the Max Planck Institute for Meteorology (MPI-M): The CMIP5 rcp85 experiment., World Data Center for Climate (WDCC) at DKRZ, https://doi.org/10.1594/WDCC/RCM_CMIP5_rcp85-LR, 2012b.

Grell, G. A., Peckham, S. E., Schmitz, R., McKeen, S. A., Frost, G., Skamarock, W. C., and Eder, B.: Fully coupled online chemistry within the WRF model, Atmospheric Environment, 39, 6957 – 6975, https://doi.org/https://doi.org/10.1016/j.atmosenv.2005.04.027, 2005.

Hamra, G. B., Guha, N., Cohen, A., Laden, F., Raaschou-Nielsen, O., Samet, J. M., Vineis, P., Forastiere, F., Saldiva, P., Yorifuji, T., and Loomis, D.: Outdoor particulate matter exposure and lung cancer: a systematic review and meta-analysis, Environmental health perspectives, 122, 906–911, https://doi.org/10.1289/ehp/1408092, 2014.

450 Hong, C., Zhang, Q., Zhang, Y., Davis, S. J., Zhang, X., Tong, D., Guan, D., Liu, Z., and He, K.: Weakening aerosol direct radiative effects mitigate climate penalty on Chinese air quality, Nature Climate Change, 10, 845–850, https://doi.org/10.1038/s41558-020-0840-y, 2020.

Hou, P., Wu, S., McCarty, J. L., and Gao, Y.: Sensitivity of atmospheric aerosol scavenging to precipitation intensity and frequency in the context of global climate change, Atmospheric Chemistry and Physics, 18, 8173–8182, https://doi.org/10.5194/acp-18-8173-2018, https://www.atmos-chem-phys.net/18/8173/2018/, 2018.

455 Im, U., Brandt, J., Geels, C., Hansen, K. M., Christensen, J. H., Andersen, M. S., Solazzo, E., Kioutsioukis, I., Alyuz, U., Balzarini, A., Baro, R., Bellasio, R., Bianconi, R., Bieser, J., Colette, A., Curci, G., Farrow, A., Flemming, J., Fraser, A., Jimenez-Guerrero, P., Kitwiroon, N., Liang, C.-K., Nopmongcol, U., Pirovano, G., Pozzoli, L., Prank, M., Rose, R., Sokhi, R., Tuccella, P., Unal, A., Vivanco, M. G., West, J., Yarwood, G., Hogrefe, C., and Galmarini, S.: Assessment and economic valuation of air pollution impacts on human health over Europe and the United States as calculated by a multi-model ensemble in the framework of AQMEII3, Atmospheric Chemistry and Physics, 18,
460 5967–5989, https://doi.org/10.5194/acp-18-5967-2018, 2018.

Jacob, D., Kotova, L., Teichmann, C., Sobolowski, S. P., Vautard, R., Donnelly, C., Koutroulis, A. G., Grillakis, M. G., Tsanis, I. K., Damm, A., Sakalli, A., and van Vliet, M. T. H.: Climate Impacts in Europe Under +1.5∘C Global Warming, Earth's Future, 6, 264–285, https://doi.org/10.1002/2017EF000710, 2018.

Jacob, D., Teichmann, C., Sobolowski, S., Katragkou, E., Anders, I., Belda, M., Benestad, R., Boberg, F., Buonomo, E., Cardoso, R. M.,
465 Casanueva, A., Christensen, O. B., Christensen, J. H., Coppola, E., De Cruz, L., Davin, E. L., Dobler, A., Domínguez, M., Fealy, R., Fernandez, J., Gaertner, M. A., García-Díez, M., Giorgi, F., Gobiet, A., Goergen, K., Gómez-Navarro, J. J., Alemán, J. J. G., Gutiérrez, C., Gutiérrez, J. M., Güttler, I., Haensler, A., Halenka, T., Jerez, S., Jiménez-Guerrero, P., Jones, R. G., Keuler, K., Kjellström, E., Knist, S., Kotlarski, S., Maraun, D., van Meijgaard, E., Mercogliano, P., Montávez, J. P., Navarra, A., Nikulin, G., de Noblet-Ducoudré, N., Panitz, H.-J., Pfeifer, S., Piazza, M., Pichelli, E., Pietikäinen, J.-P., Prein, A. F., Preuschmann, S., Rechid, D., Rockel, B., Romera, R., Sánchez, E.,
470 Sieck, K., Soares, P. M. M., Somot, S., Srnec, L., Sørland, S. L., Termonia, P., Truhetz, H., Vautard, R., Warrach-Sagi, K., and Wulfmeyer, V.: Regional climate downscaling over Europe: perspectives from the EURO-CORDEX community, Regional Environmental Change, 20, 51, https://doi.org/10.1007/s10113-020-01606-9, 2020.

Jacob, D. J. and Winner, D. A.: Effect of climate change on air quality, Atmospheric Environment, 43, 51 – 63, https://doi.org/https://doi.org/10.1016/j.atmosenv.2008.09.051, atmospheric Environment - Fifty Years of Endeavour, 2009.

475 Jerez, S., López-Romero, J. M., Turco, M., Lorente-Plazas, R., Gómez-Navarro, J. J., Jiménez-Guerrero, P., and Montávez, J. P.: On the Spin-Up Period in WRF Simulations Over Europe: Trade-Offs Between Length and Seasonality, Journal of Advances in Modeling Earth Systems, 12, e2019MS001 945, https://doi.org/10.1029/2019MS001945, 2020.

Jiménez-Guerrero, P., Montávez, J. P., Gómez-Navarro, J. J., Jerez, S., and Lorente-Plazas, R.: Impacts of climate change on ground level gas-phase pollutants and aerosols in the Iberian Peninsula for the late XXI century, Atmospheric Environment, 55, 483 – 495,
480 https://doi.org/10.1016/j.atmosenv.2012.02.048, 2012.

Jiménez-Guerrero, P., Gómez-Navarro, J. J., Baró, R., Lorente, R., Ratola, N., and Montávez, J. P.: Is there a common pattern of future gas-phase air pollution in Europe under diverse climate change scenarios?, Climatic Change, 121, 661–671, https://doi.org/10.1007/s10584-013-0944-8, 2013a.

Jiménez-Guerrero, P., Jerez, S., Montávez, J. P., and Trigo, R. M.: Uncertainties in future ozone and PM10 projections over Europe from a regional climate multiphysics ensemble, Geophysical Research Letters, 40, 5764–5769, https://doi.org/10.1002/2013GL057403, 2013b.

Kirtman, B., Power, S. B., Adedoyin, A. J., Boer, G. J., Bojariu, R., Camilloni, I., Doblas-Reyes, F., Fiore, A. M., Kimoto, M., Meehl, G., Prather, M., Sarr, A., Schär, C., Sutton, R., van Oldenborgh, G. J., Vecchi, G., and Wang, H. J.: Near-term Climate Change: Projections and Predictability, in: Climate Change 2013 - The Physical Science Basis, edited by Intergovernmental Panel on Climate Change, vol. 9781107057, pp. 953–1028, Cambridge University Press, Cambridge, https://doi.org/10.1017/CBO9781107415324.023, https://www.cambridge.org/core/product/identifier/CBO9781107415324A031/type/book{_}part, 2013.

Lamarque, J.-F., Bond, T. C., Eyring, V., Granier, C., Heil, A., Klimont, Z., Lee, D., Liousse, C., Mieville, A., Owen, B., Schultz, M. G., Shindell, D., Smith, S. J., Stehfest, E., Van Aardenne, J., Cooper, O. R., Kainuma, M., Mahowald, N., McConnell, J. R., Naik, V., Riahi, K., and van Vuuren, D. P.: Historical (1850–2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols: methodology and application, Atmospheric Chemistry and Physics, 10, 7017 – 7039, https://doi.org/10.5194/acp-10-7017-2010, 2010.

Lelieveld, J., Barlas, C., Giannadaki, D., and Pozzer, A.: Model calculated global, regional and megacity premature mortality due to air pollution, Atmospheric Chemistry and Physics, 13, 7023–7037, https://doi.org/10.5194/acp-13-7023-2013, 2013.

Lelieveld, J., Evans, J. S., Fnais, M., Giannadaki, D., and Pozzer, A.: The contribution of outdoor air pollution sources to premature mortality on a global scale, Nature, 525, 367–371, https://doi.org/10.1038/nature15371, 2015.

Lelieveld, J., Klingmüller, K., Pozzer, A., Pöschl, U., Fnais, M., Daiber, A., and Münzel, T.: Cardiovascular disease burden from ambient air pollution in Europe reassessed using novel hazard ratio functions, European Heart Journal, 40, 1590–1596, https://doi.org/10.1093/eurheartj/ehz135, 2019.

Liang, C.-K., West, J. J., Silva, R. A., Bian, H., Chin, M., Davila, Y., Dentener, F. J., Emmons, L., Flemming, J., Folberth, G., Henze, D., Im, U., Jonson, J. E., Keating, T. J., Kucsera, T., Lenzen, A., Lin, M., Lund, M. T., Pan, X., Park, R. J., Pierce, R. B., Sekiya, T., Sudo, K., and Takemura, T.: HTAP2 multi-model estimates of premature human mortality due to intercontinental transport of air pollution and emission sectors, Atmospheric Chemistry and Physics, 18, 10 497–10 520, https://doi.org/10.5194/acp-18-10497-2018, 2018.

McConnell, R., Berhane, K., Yao, L., Jerrett, M., Lurmann, F., Gilliland, F., Künzli, N., Gauderman, J., Avol, E., Thomas, D., and Peters, J.: Traffic, susceptibility, and childhood asthma, Environmental health perspectives, 114, 766–772, https://doi.org/10.1289/ehp.8594, 2006.

Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., van Vuuren, D. P., Carter, T. R., Emori, S., Kainuma, M., Kram, T., Meehl, G. A., Mitchell, J. F. B., Nakicenovic, N., Riahi, K., Smith, S. J., Stouffer, R. J., Thomson, A. M., Weyant, J. P., and Wilbanks, T. J.: The next generation of scenarios for climate change research and assessment, Nature, 463, 747–756, https://doi.org/https://doi.org/10.1038/nature08823, 2010.

NASA SocioEconomic Data and Applications Center: Basic Demographic Characteristics, v4.11, http://sedac.ciesin.columbia.edu, 2019.

Ohata, S., Moteki, N., Mori, T., Koike, M., and Kondo, Y.: A key process controlling the wet removal of aerosols: new observational evidence, Scientific Reports, 6, 34 113, https://doi.org/10.1038/srep34113, 2016.

Palacios-Peña, L., Montávez, J. P., López-Romero, J. M., Jerez, S., Gómez-Navarro, J. J., Lorente-Plazas, R., Ruiz, J., and Jiménez-Guerrero, P.: Added value of aerosol-cloud interactions for representing aerosol optical depth in an online coupled climate-chemistry model over Europe, Atmosphere, 11(4), 360, https://doi.org/https://doi.org/10.3390/atmos11040360, 2020.

Park, S., Allen, R. J., and Lim, C. H.: A likely increase in fine particulate matter and premature mortality under future climate change, Air Quality, Atmosphere & Health, 13, 143–151, https://doi.org/10.1007/s11869-019-00785-7, 2020.

Pope, C. A., Burnett, R. T., Krewski, D., Jerrett, M., Shi, Y., Calle, E. E., and Thun, M. J.: Cardiovascular mortality and exposure to airborne fine particulate matter and cigarette smoke, Circulation, 120, 941–948, https://doi.org/10.1161/CIRCULATIONAHA.109.857888, 2009.

Pope, C. A., Coleman, N., Pond, Z. A., and Burnett, R. T.: Fine particulate air pollution and human mortality: 25+ years of cohort studies, Environmental Research, 183, 108 924, https://doi.org/10.1016/j.envres.2019.108924, 2020.

Prüss-Üstün, A., Wolf, J., Corvalán, C. F., Bos, R., and Neira, M. P.: Preventing disease through healthy environments: a global assessment of the burden of disease from environmental risks, World Health Organization, 2016.

Silva, R. A., West, J. J., Zhang, Y., Anenberg, S. C., Lamarque, J.-F., Shindell, D. T., Collins, W. J., Dalsoren, S., Faluvegi, G., Folberth, G., Horowitz, L. W., Nagashima, T., Naik, V., Rumbold, S., Skeie, R., Sudo, K., Takemura, T., Bergmann, D., Cameron-Smith, P., Cionni, I., Doherty, R. M., Eyring, V., Josse, B., MacKenzie, I. A., Plummer, D., Righi, M., Stevenson, D. S., Strode, S., Szopa, S., and Zeng, G.: Global premature mortality due to anthropogenic outdoor air pollution and the contribution of past climate change, Environmental Research Letters, 8, 034 005, https://doi.org/10.1088/1748-9326/8/3/034005, 2013.

Silva, R. A., Adelman, Z., Fry, M. M., and West, J. J.: The Impact of Individual Anthropogenic Emissions Sectors on the Global Burden of Human Mortality due to Ambient Air Pollution, Environmental Health Perspectives, 124, 1776–1784, https://doi.org/10.1289/EHP177, 2016a.

Silva, R. A., West, J. J., Lamarque, J.-F., Shindell, D. T., Collins, W. J., Dalsoren, S., Faluvegi, G., Folberth, G., Horowitz, L. W., Nagashima, T., Naik, V., Rumbold, S. T., Sudo, K., Takemura, T., Bergmann, D., Cameron-Smith, P., Cionni, I., Doherty, R. M., Eyring, V., Josse, B., MacKenzie, I. A., Plummer, D., Righi, M., Stevenson, D. S., Strode, S., Szopa, S., and Zengast, G.: The effect of future ambient air pollution on human premature mortality to 2100 using output from the ACCMIP model ensemble, Atmospheric Chemistry and Physics, 16, 9847–9862, https://doi.org/10.5194/acp-16-9847-2016, 2016b.

Silva, R. A., West, J. J., Lamarque, J.-F., Shindell, D. T., Collins, W. J., Faluvegi, G., Folberth, G. A., Horowitz, L. W., Nagashima, T., Naik, V., Rumbold, S. T., Sudo, K., Takemura, T., Bergmann, D., Cameron-Smith, P., Doherty, R. M., Josse, B., MacKenzie, I. A., Stevenson, D. S., and Zeng, G.: Future global mortality from changes in air pollution attributable to climate change, Nature Climate Change, 7, 647–651, https://doi.org/10.1038/nclimate3354, 2017.

Tarín-Carrasco, P., Morales-Suárez-Varela, M., Im, U., Brandt, J., Palacios-Peña, L., and Jiménez-Guerrero, P.: Isolating the climate change impacts on air-pollution-related-pathologies over central and southern Europe – a modelling approach on cases and costs, Atmospheric Chemistry and Physics, 19, 9385–9398, https://doi.org/10.5194/acp-19-9385-2019, 2019.

Tarín-Carrasco, P., Im, U., Geels, C., Palacios-Peña, L., and Jiménez-Guerrero, P.: Contribution of fine particulate matter to present and future premature mortality over Europe: a non-linear response, Environment International, https://doi.org/Submitted, 2020.

United Nations: Department of Economic and Social Affairs Population Dynamics, https://population.un.org/wpp/, 2020.

Vedal, S., Han, B., Xu, J., Szpiro, A., and Bai, Z.: Design of an air pollution monitoring campaign in beijing for application to cohort health studies, International Journal of Environmental Research and Public Health, 14, 1580, https://doi.org/https://doi.org/10.3390/ijerph14121580, 2017.

World Health Organization: Review of evidence on health aspects of air pollution -REVIHAAP Project: Technical Report, World Health Organization, p. 301, https://doi.org/10.1007/BF00379640, http://www.euro.who.int/pubrequesthttp://www.euro.who.int/en/health-topics/environment-and-health/air-quality/publications/2013/review-of-evidence-on-health-aspects-of-air-pollution-revihaap-project-final-technical-report, 2013.