Author's Response to the Interactive comment on **"Isolating the climate change impacts on air pollution-related-pathologies over Europe – A modelling approach on cases and costs (acp-2019-21)"** submitted by Patricia Tarín-Carrasco et al.

A: First, we would like to thank the anonymous referees for their valuable comments in the interactive comment on "Isolating the climate change impacts on air pollution-related-pathologies over Europe – A modelling approach on cases and costs" by Patricia Tarín-Carrasco et al. The manuscript has been revised after the reviewer's comments in order to correct errors and to introduce the reviewers' suggestions for improving the quality of the paper. Please see below our point-by-point replies:

Anonymous Referee #1

R#1: This work described the climate change impacts on air pollution-related-pathologies over Europe with a modelling approach on cases and costs. Although this study provides important results and is well written, there remain some concerns in the current manuscript. It would be important to restructure the paper in results/discussion/conclusions [...].I strongly recommend the authors to include a limitation section about the applied methods for the epidemiological relationship and modelling of the climate change scenarios [...]

A: We strongly appreciate the valuable comments of Reviewer #1. An effort has been made to rewrite the paper, separating the results and discussion section from the conclusions. Moreover, in the conclusions, a brief section has been included trying to highlight the limitations of this work.

R#1: Pag 2. Line 10: I'm missing an important reason. The main issue with pollution is the spatio-temporal variability from local to global scales.

A: We agree with the reviewer's suggestion. This has been added in the revised version of the manuscript.

R#1: Pag 3. Line 10: "Héroux et al. (2015) suggest that mortality risk associated to air pollution can be reversible on a short period."

In this context, it would be important to difference short and long-term effects. [...] It is also important to highlight that the cost for the health system of the impacts with lower severity and greater population affected can overcome of those situations that have a greater seriousness but a smaller affected population (EEA 2013. Environment and human health, Joint EEA-JRC report Nr 5 Report EUR 25933 EN). Another aspect would be the vulnerable groups (elderly, people with chronic diseases and children). In an aging society, even if the exposure were reducing, more people would be at risk and vulnerable in the future.

A: We strongly appreciate these valuable comments of Reviewer #1. This has been added in the revised version of the manuscript.

R#1: Pag 3. Line 16: Why you use only scenario (2071-2100, RCP8.5)? See Fig. 4 from
https://www.atmos-chem-phys.net/18/15471/2018/acp-18-15471-2018.pdf

A: We strongly appreciate the valuable comments of Reviewer #1. In this work, we used chemistry-climate simulation which covers a part of Europe during 30 of years. This type of simulations, which takes into account atmospheric chemistry and its interactions with meteorological variables, are computationally more expensive than an ordinary climate simulation. Therefore, the RCP8.5 scenario was chosen because it lies at the top of the representative concentration pathways and is estimated to give the largest changes in radiative forcing and then a stronger climatic signal.

R#1: Pag 3. Line 31: Which method you used for detrending? Usually in time series regression, you have to control cofounder variables as temperature, which has significant effects on mortality simultaneously. See Bhaskaran et al. (2013). and Analitis et al. (2018).

A: We strongly appreciate the valuable comments of Reviewer #1. The suggested references, together with further literature revision, have been included in the revised version of the manuscript.

We use the first-differences method for detrending the time series. This has been stated in the manuscript:

"According to Bashkaran et al. (2013), time series regression studies have been widely used in environmental epidemiology, notably in investigating the associations between exposures such as air pollution and health outcomes. Typically, for both exposure and outcome, data are available at regular time intervals. In our case, an epidemiological study for present situation has been carried out, with data obtained from the European Commission (Eurostat) (https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Health) corresponding to the years 2001-2012. Total Death (TD) and Death caused by Respiratory Diseases (DRD) have been analysed. The objective is to search the correlation between such mortalities and air pollution (in our study case, PM10, due to the short time series available for PM2.5). Although mortality data was available since 1994, the targeted period begins in 2001 due to the availability of PM10 data. As on Analitis et al. (2018), a first order correlation structure was employed" […] *"The correlation is not done directly on the raw data, but the anomalies of mortality and PM10 series. These series are detrended in order to avoid spurious correlations. The detrending method is based on the first-time difference time series and is widely used in climate data analysis (e.g. Lobell and Field, 2007; Zhao et al., 2017). Linear regressions are performed with first differences in TD and DRD as the response variable, and first differences of PM10 as the predictor variable. The regressions found have undergone a Mann-Kendall test in order to assure their significance at 95% confidence (p<0.05)."*
"

However, we are aware about the cofounder variables, but the objective of this study is not to do an epidemiological study. The objective to use these series was to show the presence of a correlation between the pollutans and the pathologies and then to use this correlation to estimate the number of mortality due these pollutants.

R#1: Pag 4. Line 10: Which is your study area? If Europe, than why you only use most of southern and central Europe?

A: We agree with the reviewer's suggestion. The title could lead to confusion because the domain does not cover Europe entirely. For this reason, the title has been modified by : "Isolating the climate change impacts on air pollution-related-pathologies over central and southern Europe – A modelling approach on cases and costs"

R#1: Pag 5-6. 3.1: Can you discuss with more detail the absence of correlation in some countries, which could be also due to the high spatio-temporal variability and methods issue (in comparison with local epidemiological studies). Discuss limitation of methods in another point and compare you results with city-specific studies.

A: We strongly appreciate the valuable comments of Reviewer #1. This has been added in the revised version of the manuscript.

R#1: Pag 15. Line 30: "we should bear in mind the aging of European population and the increase of city dwellers, variables that have not been taken into account in this study in order just to isolate the effect of climate change alone in the health of European citizens."This is an important aspect and you should discuss it with more detail, in particular, which consequences has this for your results and the limitation of not including a population projection.

A: We agree with the reviewer's suggestion. However, the objective of this work is to isolate the effect of climate change to the dwellers wellness. For that reason, we have added the reviewer's suggestion in the revised version of the manuscript.

R#1: Minor comments: Maps. I would suggest using a different projection for Europe. For example, "+proj=laea +lat_0=52 +lon_0=10 +x_0=4321000 +y_0=3210000+ellps=GRS80 +units=m +no_defs"

A: Maps have been re-done by using the suggested projection and included in the the revised version of the manuscript.

Anonymous Referee #2

R#2: It is not clear to the reader how the authors estimated the present and future costs of air pollution. The authors should explain in detail the methods used to estimate those costs and how they extrapolated their estimates for the future scenario for each country.

A: We strongly appreciate the valuable comments of Reviewer #2. We followed the methodology of Brand et al. 2013a and 2013b. This is summarized in the manuscript and the formula are compiled on Table 1.

R#2: The authors used for the epidemiology study a dataset of 25 European countries. Is this compatible with the domain analysed with WRF-Chem? What are the assumptions made here?

A: Please see the answer in Reviewer #1's comments. Some of the countries used in the epidemiology study lie out of our simulation domain; that is why the methodology is complementary. In order to avoid confusion, we have changed the name of the manuscript.

R#2: A basic limitation here is that the study assumes the population constant for the future scenario. As a robustness check it would help to run a second simulation that takes into account the projected population. Another limitation of the study is that economy also changes thus affecting air pollution levels. This could also be included in the limitations of the study

A: We strongly appreciate the valuable comments of Reviewer #2. However, this suggestion is slightly beyond the scope of this contribution. The objective of this work was to show how the climate change is going to affect dwellers wellness, hence, we isolate the action of climate change. If population had been changed, it would be difficult to assess the impact of climate penalty itself. That is why we decided to keep population constant.

However, there is another manuscript under writing nowadays (that will complement the present submission) including both the changes in population and the scenario emissions (which take into account changes in the economy).

Isolating the climate change impacts on air pollution-related-pathologies over central and southern Europe - A modelling approach on cases and costs

Patricia Tarín-Carrasco[1], María Morales-Suárez-Varela[2,3], Ulas Im[4], Jørgen Brandt[4], Laura Palacios-Peña[1], and Pedro Jiménez-Guerrero[1,5]

[1]Department of Physics, Regional Campus of International Excellence Campus Mare Nostrum, University of Murcia, Murcia, Spain
[2]2Unit of Public Health and Environmental Care, Department of Preventive Medicine, University of Valencia, Valencia, Spain
[3]CIBER Epidemiology and Public Health (CIBERESP), Madrid, Spain
[4]Aarhus University, Department of Environmental Science, Frederiksborgvej 399, DK-4000, Roskilde, Denmark
[5]Biomedical Research Institute of Murcia (IMIB-Arrixaca), 30120 Murcia, Spain

Correspondence: Pedro Jiménez-Guerrero (pedro.jimenezguerrero@um.es)

Abstract.

Air pollution has important implications on human health and associated external costs to society, and is closely related to climate change. This contribution tries to assess the impacts of present (1996-2015) and future (2071-2100 under RCP8.5) air pollution on several cardiovascular and respiratory pathologies and to estimate the difference in the costs associated to those health impacts on European population. For that, air quality data from the WRF-Chem regional chemistry/climate modelling system is used, together with some epidemiological information from the European Commission. The methodology considered relies on the EVA exposure-response functions and economic valuations (Brandt et al., 2013a, b). Several hypothesis have been established, in order to strictly isolate the effects of climate change on air pollution and health: constant present-day emission levels and population density in all Europe. In general, the number of cases for the pathologies considered will increase in the future (chronic bronchitis, heart failure, lung cancer, premature deaths), increasing the overall cost associated from 173 billion €/year to over 204 billion €/year at the end of the present century. Premature deaths are the most important problem in the target area in terms of costs (158 billion €per year, increasing by 17% in the future RCP8.5 2071-2100 projection) and cases (418 700 cases/year, increasing by 94 900 cases/year in the future). The most affected areas are European megacities, the Ruhr Valley and several cities at eastern Europe (e.g. Chisinau, Bucharest). For the RCP8.5 scenario, cases and costs will increase over southern and eastern Europe, while central and northern Europe could benefit by climate change variations (decreasing both cases and costs for the studied pathologies).

1 Introduction

Nowadays, air pollution is a serious environmental concern with a severe impact on population: on the one hand, by its close relationship with climate change; and on the other hand, because of its effects on human health and welfare. Air pollution is

an environmental problem affecting the entire planet, either by local or transboundary pollution (Ravishankara et al., 2012). In 2012, 3.7 million of premature deaths were caused by exposition to air pollution worldwide (WHO, 2013). In addition, indirectly, air pollution, has external costs to society related to damages to human health. For this reason, the control of emissions of atmospheric pollutants and having reliable future air quality estimations can represent a good strategy for mitigating air pollution-related pathologies (Lelieveld et al., 2015). However, European targets for emissions and air pollution are not reached in southern Europe not only because of anthropic emissions, but also by natural causes (Pozzer et al., 2012), being the Mediterranean Basin the most affected area by increases in air pollution in present and future climate scenarios (Colette et al., 2012; Jiménez-Guerrero et al., 2013a).

Quantifying premature death caused by air pollution is difficult for several reasons. First, the lack of monitoring stations; second, the variable toxicity of pollutants depending on their nature; and third the spatio-temporal variability from local to global scales (Lelieveld et al., 2015). The effects of pollutants on the population also depend on its composition, exposition time and health condition of dwellers. Life habits must be as well considered: for instance, Stieb et al. (2017) recommended to reduce exposure time and physical activity outdoor under episodes with high concentrations of air pollutants. Moreover, the diverse combination of air pollutants can have additives or synergists adverse effects on health (Curtis et al., 2006). Another factor hampering the attribution of deaths or different pathologies caused by air pollution is its association with high temperatures (Pearce et al., 2016). These authors indicate the relationship between high temperature short-term exposition and mortality risk. Therefore, heat extreme events are another aspect to ~~contemplate~~ take into account for population health under a changing climate.

Pollutants of largest concern for human health in Europe are particulate matter (PM) with a diameter lower than 2.5 microns (PM2.5), nitrogen oxides (NO_x), sulfur dioxide (SO_2), tropospheric ozone (O_3) and carbon monoxide (CO) (Pozzer et al., 2012). Both O_3 and PM are related with cardiorespiratory diseases and premature death. The most important pollutant for the mortality is PM, with an important decrease on the life expectancy projected for future scenarios (Héroux et al., 2015). PM exposure, especially to fine particles (PM2.5), may severely affect human health (Brook et al., 2010), piercing up lungs or even pulmonary alveoli (Pope and Dockery, 2006). They produce cardiorespiratory symptoms and illness, increased asthma cases, heart attacks, stroke, and even premature mortality (Tagaris et al., 2010). Fine particles can produce damage even in small concentrations (Beelen et al., 2014). Giannadaki et al. (2017) estimated premature deaths caused by PM2.5 at 3.15 million/year in 2010 globally, while their estimation for Europe was around 173 000 premature deaths (about 5% of the global rate). Gaseous pollutants like NO_x or SO_2 may get in the organism by inhalation and affect respiratory system, irritating the respiratory system, and inducing bronchoconstriction and asthma (Kampa and Castanas, 2007).

Recently, Im et al. (2018) estimated the health impacts of air pollution in Europe and the United States (US) by using concentration inputs from different chemistry-transport models in the Economic Valuation of Air Pollution (EVA) system (Brandt et al., 2013a, b). In Europe, the total number of premature deaths (acute and chronic) and associated costs is calculated to be 414 000 and 300 billion€, respectively.

In addition, climate change alone may affect the concentration of these gaseous pollutants and particles through modifications on chemistry on gaseous phase, transport, deposition and natural emissions (Jacob and Winner, 2009). Modelling

approaches (together with remote sensing) may represent a good methodology to disentangle the role of climate change on air pollution and get future projections of air quality (Jerrett et al., 2017).

Due to changes on the future climatic conditions, air quality will importantly worsen, especially in southern Europe (Jiménez-Guerrero et al., 2013a). Several studies have combined atmospheric science, epidemiology, public health and economy and ~~tries~~ have tried to asses future air pollution, mitigation strategies and its relation and repercussions on population health and associated costs. For instance, Geels et al. (2015) ~~indicate~~ indicated that climate change effect together with a reduction of emissions will decrease the premature deaths caused by air pollution. These authors estimated a reduction for acute mortality caused by PM in a 36%-64% for 2050s and 53%-84% for 2080s; and a decrease of 62%-65% and almost 80% for same future periods if chronic mortality is targeted. ~~Héroux et al. (2015)~~ Short and long-term exposition to pollutants can be reversible (Héroux et al., 2015). These authors suggest that mortality risk associated to air pollution can be reversible on such a short period ~~,~~ as a year. The human body can partially recover when the exposition to the pollutant concentration ends. The cost for the health system of the impacts with lower severity and a larger number of dwellers affected can exceed the impacts of more acute situations (higher concentration of pollutants) but a smaller number of affected population (EEA, 2013).

Henceforth, this study focuses on the analysis of population health problems caused by regulatory pollutants in Europe ~~,~~ and their associated costs. First, the methodology followed tries to get the correlation (if any) between particles with a diameter under 10 microns (PM10) and total deaths and deaths caused by respiratory diseases over Europe, by using epidemiological data from the European Commission for the period 2001-2012. Then, in order to assess the impact of air pollution on health for present and future scenarios, data from a regional chemistry/climate model for a present climatology (1996-2015) will be used for estimating the cases and associated costs of some related pathologies and the differences found for a future climate scenario (2071-2100, RCP8.5).

2 Methodology

2.1 Epidemiological study for present-climate situation

~~First,~~ According to Bashkaran et al. (2013), time series regression studies have been widely used in environmental epidemiology, notably in investigating the associations between exposures such as air pollution and health outcomes. Typically, for both exposure and outcome, data are available at regular time intervals. In our case, an epidemiological study for present situation has been carried out, with data obtained from the European Commission (Eurostat) (https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Health) corresponding to the years 2001-2012. Total Death (TD) and Death caused by Respiratory Diseases (DRD) have been analysed. The objective is to search the ~~relationship~~ correlation between such mortalities and air pollution (in our study case, PM10, due to the short time series available for PM2.5). Although mortality data was available since 1994, the targeted period begins in 2001 due to the availability of PM10 data. As on Analitis et al. (2018), a first order correlation structure was employed.

This study covers 25 European countries in total, with a non-homogeneous time coverage because the different year of entry into the European Union. Taking into account the data availability, the countries selected for the epidemiology analysis

were Austria, Belgium, Bulgaria, Czech Republic, Denmark, Estonia, Finland, France, Germany, Hungary, Iceland, Ireland, Italy, Luxembourg, The Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland and United Kingdom.

The correlation is not done directly on the raw data, but the anomalies of mortality and PM10 series. These series are de-trended in order to avoid spurious correlations. ~~With the anomaly series , a correlation between total mortality and PM10 and between deaths caused by respiratory disease and such pollutant is carried out. The correlations~~ The detrending method is based on the first-time difference time series and is widely used in climate data analysis (e.g. Lobell and Field (2007); Zhao et al. (2017)). Linear regressions are performed with first differences in TD and DRD as the response variable, and first differences of PM10 as the predictor variable. The regressions found have undergone a Mann-Kendall test in order to assure their significance at 95% confidence ($p<0.05$).

2.2 Regional chemistry/climate simulations

In addition, air quality model data is used in order to check the possible changes in pathologies and diseases between present and future scenarios of climate change. The simulations used for assessing air quality in this work span the periods 1996-2015, as a present reference period, and 2071-2100 under the RCP8.5 scenario, as a future enhanced forcing scenario. This scenario is at the top of radiative forcing scenarios among all the Representative Concentration Paths (Moss et al., 2010), and hence the largest effect on the concentration of air pollutants is expected. The differences between these two runs (present and RCP8.5) will provide the changes in future air quality.

The regional chemistry/climate model used has been WRF-Chem (Grell et al., 2005). The spatial model configuration comprises a domain covering most of southern and central Europe with a resolution of 25 km for WRF-Chem simulations. Thirty-three sigma levels are considered in the vertical, with the top of the atmosphere at 50 hPa. Historical simulations with WRF-Chem (1996-2015) were driven by the ERA20C reanalysis (Poli et al., 2016), whose approximate resolution is 125 km; and the 200-km resolution CMIP5-experiment r1i1p1 MPI-ESM-LR (Taylor et al., 2012; Giorgetta et al., 2012a). No nudging was conducted on the experiments. The CMIP5-experiment RCP8.5-forced r1i1p1 MPI-ESM-LR run (Giorgetta et al., 2012b) was used for the scenario period (2071-2100)

Further information on the physico-chemical configuration of the model can be found in the scientific literature (Forkel et al., 2015; Palacios-Peña et al., 2017). A short description is presented here. The WRF-Chem setup used in these simulations include the following options: RADM2 chemical mechanism; MADE/SORGAM aerosol module including some aqueous reactions; Fast-J photolysis scheme; RRTMG shortwave and longwave radiation schemes; Yonsei University PBL scheme (YSU) for the Planetary Boundary Layer; dry deposition follows the Wesely resistance approach, while wet deposition is divided into convective wet deposition and grid-scale wet deposition.

The modelling system for present-day climatologies has been extensively evaluated (Brunner et al., 2015). Despite the model skills with respect to air pollution modelling data used for health estimations are widely discussed (Im et al., 2018), more information with respect to ozone and particulate matter (PM10) can be found in Im et al. (2015a, b).

In order to isolate the possible effects of climate change alone on air pollutants, unchanged anthropogenic emissions coming from ACCMIP (Lamarque et al., 2010) are assumed. That allows to anticipate the possible impacts if no mitigation strategies for regulatory pollutants are carried out and characterize the climate penalty on air quality levels. Natural emissions depend on climate conditions, and therefore vary in present and future simulations. Hence, the effects of climate change on air pollution

5   follow the methodology explained in (Jiménez-Guerrero et al., 2013b), excluding possible changes in vegetation or land use.

2.3   Present and future impacts of air quality on pathologies

The impact of air quality on the following pathologies is contemplated in this work: Respiratory Hospital Admissions (RHA), Cerebrovascular Hospital Admissions (CHA), Congestive Heart Failure (CHF), Chronic Bronchitis (CB), Lung Cancer (LC) and Premature Deaths (PD), this latter related both to acute mortality and chronic mortality as defined in ~~(Brandt et al., 2013a, b)~~

10   Brandt et al. (2013a, b).

For that, the gridded population data has been obtained from the SocioEconomic Data and Applications Center (SEDAC) of NASA (http://sedac.ciesin.columbia.edu) at a resolution of 1 km^2 and interpolated to the working grid. Since the time coverage of our analysis is 1996-2015, the Population Density, v4 dataset for the year 2005 has been used, based on counts consistent with national censuses and population registers. The population by cell is shown in Fig. 1. For the future scenario,

15   the population has been kept constant in order to have an educated guess of the possible impacts due only to changes in air quality.

In order to calculate the air quality impacts on the aforementioned pathologies, the methodology described in the EVA system (Brandt et al., 2013a, b), and references therein, has been used. In this work, we have utilized the population from SEDAC together with the WRF-Chem simulations and the exposure-response functions and economic valuations (as 2006

20   euros) compiled in Brandt et al. (2013a) to estimate external costs of air pollution. The exposure-response coefficient and the valuation used are compiled in Table 1.

3   Results and Discussion

3.1   Statistical epidemiological study for present situation

In the following section the results from ~~collected data from Eurostat~~ Eurostat data have been analysed. After detrending

25   the data and calculating the anomalies for Total Death (TD), Deaths by Respiratory Diseases (DRD) and PM10, correlations for each country between mortality and particles have been established. The obtained results are shown on Table 2, where bold values indicate correlations significant at 95% confidence interval (p<0.05). Countries as Germany, Hungary, Italy and Slovenia present a clear relation between such pollutant and both TD and DRD, with a high correlation in the anomaly series and high statistical significance. Meanwhile, countries as Czech Republic, Estonia or Switzerland present a notable statistically-

30   significant correlation only for TD-PM10 correlation. For the rest of the countries, mainly due to the short time series of data, either no significance (e.g. Bulgaria, Denmark, France, United Kingdom, Spain, Iceland) or a significant very low correlation

Table 1. Pathology, exposure-response coefficients and economic valuation, taken from Brandt et al. (2013a).

Pathology	Exposure-response coefficient	Valuation
Respiratory Hospital Admissions (RHA)	3.46×10^{-6} cases / μg m^{-3} PM	
	$+ 2.04 \times 10^{-6}$ cases / μg m^{-3} SO$_2$	7931€/case
Cerebrovascular Hospital Admissions (CHA)	8.42×10^{-6} cases / μg m^{-3} PM	10047€/case
Congestive Heart Failure (CHF)	3.09×10^{-5} cases / μg m^{-3} PM	
	$+ 5.64 \times 10^{-7}$ cases / μg m^{-3} CO	16409€/case
Chronic Bronchitis (CB)	8.20×10^{-5} cases / μg m^{-3} PM	52962€/case
Lung Cancer (LC)	1.26×10^{-5} cases / μg m^{-3} PM	21152€/case
Premature Deaths (PD)	3.27×10^{-6} SOMO35 cases / μg m^{-3}	
	$+ 7.85 \times 10^{-6}$ cases / μg m^{-3} SO$_2$	2111888€/case
	$+ 1.138 \times 10^{-3}$ YOLL/ μg m^{-3} (>30 yr)	77199€/YOLL

Population by 25 x 25 km grid (in miles of habitants)
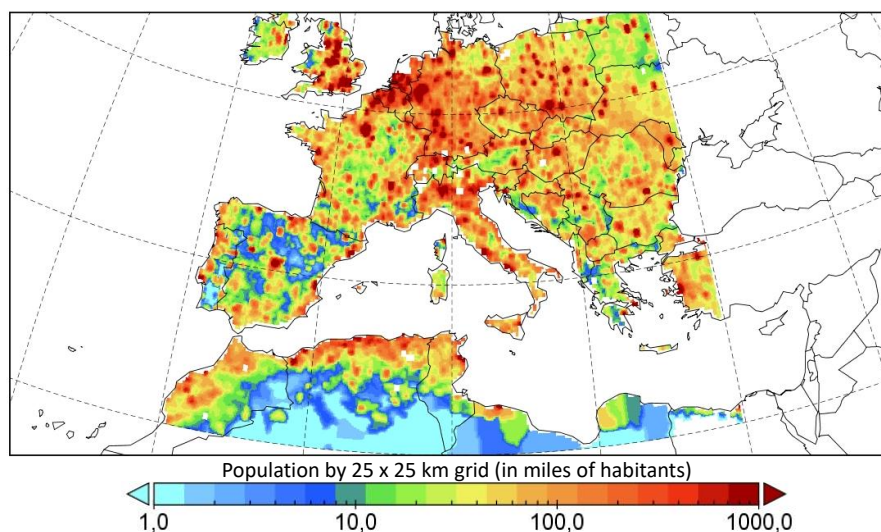
Figure 1. Population in each grid cell (in miles thousands of habitants) (SEDAC population dataset for 2005).

(e.g. Austria, The Netherlands, Sweden) is obtained. The lack of correlation in some countries could be due to a large number of factors; among them, the high spatio-temporal variability of air pollution and mortality data (that is not taken into account in nationwide information), or some methodological limitations such as the large time scale of the data series, the limited number of years with data available hampering the significance of the series, etc.

Table 2. Correlations data between Total Death (TD) and PM10 (left column) and Deaths by Respiratory Diseases (DRD) and PM10 (right column) for European countries. Bold values indicate a significant correlation (p<0.05).

Country	TD-PM10	DRD-PM10
Austria	**0.047**	**0.313**
Belgium	**0.071**	0.051
Bulgaria	-0.363	-0.225
Czech Republic	**0.455**	**0.313**
Denmark	**0.114**	-0.261
Estonia	**0.407**	-0.391
Finland	**0.168**	-0.155
France	0.230	0.272
Germany	**0.522**	**0.512**
Hungary	**0.492**	**0.678**
Iceland	-0.387	-0.649
Ireland	-0.104	**0.240**
Italy	**0.508**	**0.747**
Luxembourg	0.503	-0.105
Netherlands	**0.086**	**0.128**
Norway	-0.020	0.400
Poland	-0.125	0.095
Portugal	-0.579	-0.571
Romania	-0.146	-0.340
Slovakia	**0.258**	**0.273**
Slovenia	**0.525**	**0.418**
Spain	0.322	0.243
Sweden	**0.199**	0.195
Switzerland	**0.351**	**0.169**
United Kingdom	-0.034	-0.050

5   Hence, for several countries (despite the short data series) we can establish a relationship between mortality (especially, TD) and atmospheric PM10 levels. Generally, the correlation TD-PM10 is higher than for DRD-TD. As pointed out by several

authors, the justification for these higher correlation values can be found in mortality by PM10 being caused other pathologies that are not just respiratory, like cardiac, cerebrovascular, etc. (Curtis et al., 2006; Tagaris et al., 2010; Pozzer et al., 2012).

3.2 Present and future scenarios study for the pathologies and costs related to air pollution

This section discusses the results found for cases distribution (number of people) with different pathologies caused by several air pollutants for a present climate (1996-2015) and the differences with future RCP8.5 scenario (2071-2100). A summary of the global cases and associated costs is shown in Table 3.

Table 3. Mean number of cases (in miles of cases) as associated costs (in million €) per year for each pathology for present climate conditions (1996-2015) and variations in the future RCP8.5 scenario (2071-2100) for the entire domain of simulation.

Pathology	Cases ($\times 10^3$) (1996-2015)	ΔCases ($\times 10^3$) (2071-2100)	Costs (M€) (1996-2015)	ΔCosts (M€) (2071-2100)
Respiratory Hospital Admissions (RHA)	16.4	+3.8	87.1	+20.5
Cerebrovascular Hospital Admissions (CHA)	31.9	+7.9	214.8	+53.1
Congestive Heart Failure (CHF)	117.1	+28.9	1 288.3	+318.3
Chronic Bronchitis (CB)	310.6	+76.8	11 982	+2 962.8
Lung Cancer (LC)	47.7	+11.8	764.7	+189.1
Premature Deaths (PD)	418.7	+94.9	158 970	+27 346.0

3.2.1 Respiratory Hospital Admissions (RHA)

The results for the European domain targeted (Table 3) indicate 16400 cases of RHA per year in the 1996-2015 period, which will increase by 3800 cases in RCP8.5 2071-2100 scenario. The external costs associated to this pathology represent 87.1 M€ in the present climate, increasing in the future scenario by 20.5 M€ (that is, an increase in cases and costs of +23%).

If local differences in RHA are searched (Fig. ??2), the highest number of present cases is found in the north of the study area, in countries such Belgium, Netherlands or in the western zones of Germany. Several hotspots appear in Paris and Bucharest, with an average of 200 cases per year and cell in 1996-2015. The cases with the lowest values are found in northern Spain and central France, with less than 0.25 cases/year cell. With respect to the future (2071-2100) differences, and despite the global increase of the cases for Europe, strong differences appear between southern and northern Europe. Over central/northern Europe a slight decrease in RHA cases is projected (up to -4 cases/year cell) on localized cities located in Germany -Berlin- or Austria -Vienna-, meanwhile RHA cases may increase up to 122 per year and cell in southern and eastern Europe.

The costs follow the same spatial pattern as the cases, as expected. Despite the economic impacts on the society are limited, for several European megacities as Paris, Cologne or Bucharest the present cost of RHA may reach up to 1 M€. For the future scenario, external costs are expected to increase in various European areas, especially on eastern Europe, area which barely had
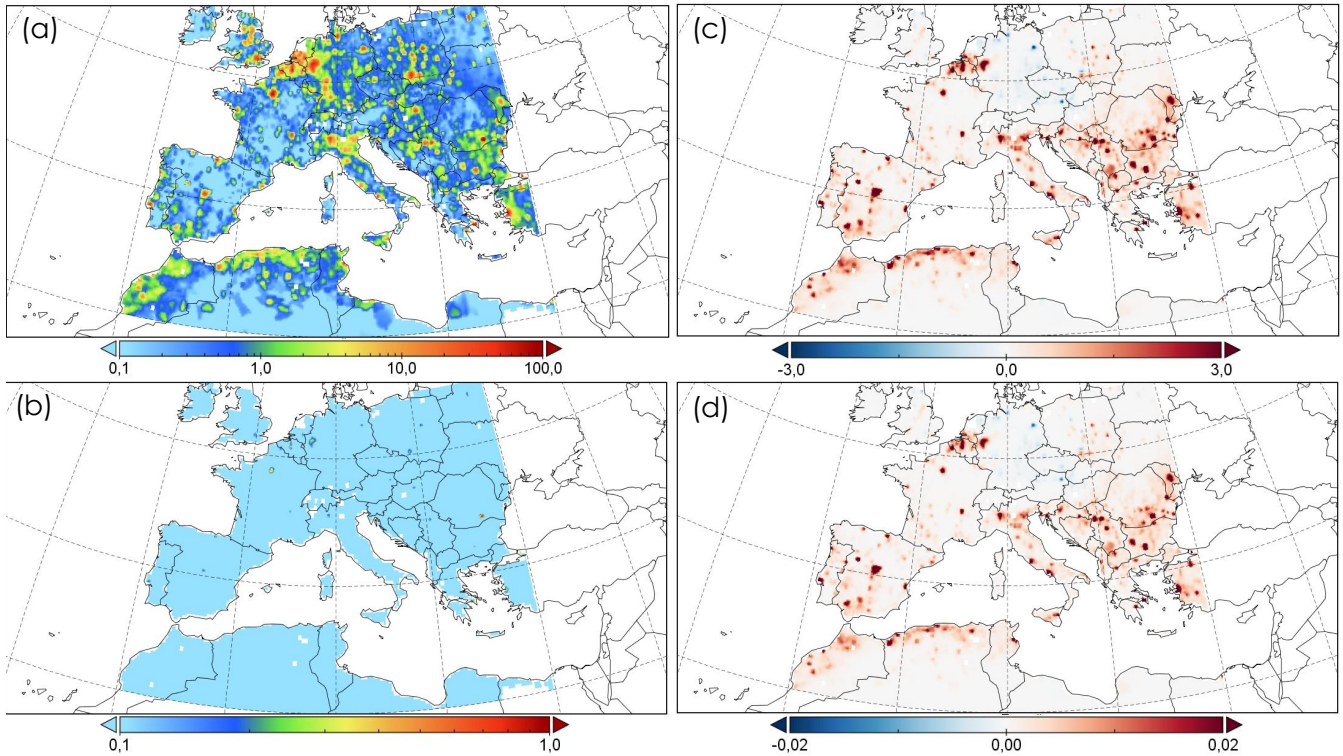
Figure 2. (~~Left columna~~) ~~(Top)~~ Present cases by Respiratory Hospital Admissions (RHA) and (~~bottomb~~) associated costs, in M€. (~~Right columnc~~) Changes projected in RHA cases _and_ (~~topd~~) ~~and~~ changes in costs (~~bottom) (~~M€) under the RCP8.5 scenario (2071-2100).

costs associated in the present climatology; or in southern countries like Spain and Italy. In this latter areas, the costs increase in more than 0.5 M€ per year and cell for 2071-2100 with respect to the 1996-2015 period.

RHA depends both on PM levels and SO_2 (also included in PD estimation). The areas with a larger impact on future RHA are those zones where power plants and other facilities of energy production are locted. In that case, the impacts on eastern countries

5   are higher due to the high sulfur-content fuels in which they base their economy (Colette et al., 2012; Pozzer et al., 2012; Geels et al., 2015) . Henceforth, most of hospital admissions are located in European megacities and eastern Europe, with poor air quality levels causing respiratory damage.

3.2.2 Cerebrovascular Hospital Admission (CHA)

Table 3 indicate a total number of 31900 cases of RHA per year in the 1996-2015 period (external cost of 214.8 M€), with

10   an associated increase for all the domain of 7900 cases in RCP8.5 2071-2100 scenario (increase in costs: 53.1 M€). That is, overall cases and costs will increase by +25% at the end of the XXI century with respect to the present situation.

Regarding ~~spatial distributed~~ spatially-distributed CHA, up to 400 cases per year are found in the city of Bucharest (Fig. ~~2~~3), with an associated external cost of 2.5 M€. Many of the European megacities exceed the 100 cases for the present period. The

9

countries with highest admission numbers are Belgium, The Netherlands and Germany. On the other hand, the northern half of Iberian Peninsula is the area least affected by CHA pathology. With respect to the differences with 2071-2100 RCP8.5 scenario, the spatial pattern follows the same structure as for RHA cases shown in Fig. ~~??~~2, as previously commented: a general increase in southern Europe (up to 270 cases per year and cell) and a light decrease mainly in cities of The Netherlands, Germany and Austria (up to 10 less cases per year and cell). The increase in costs in the future scenario can reach up to +2 M€ in large cities such as Madrid, Bucarest or Paris, while the decrease of the costs in areas with reduced CHA such as Berlin or Vienna do not exceed the -0.5 M€.
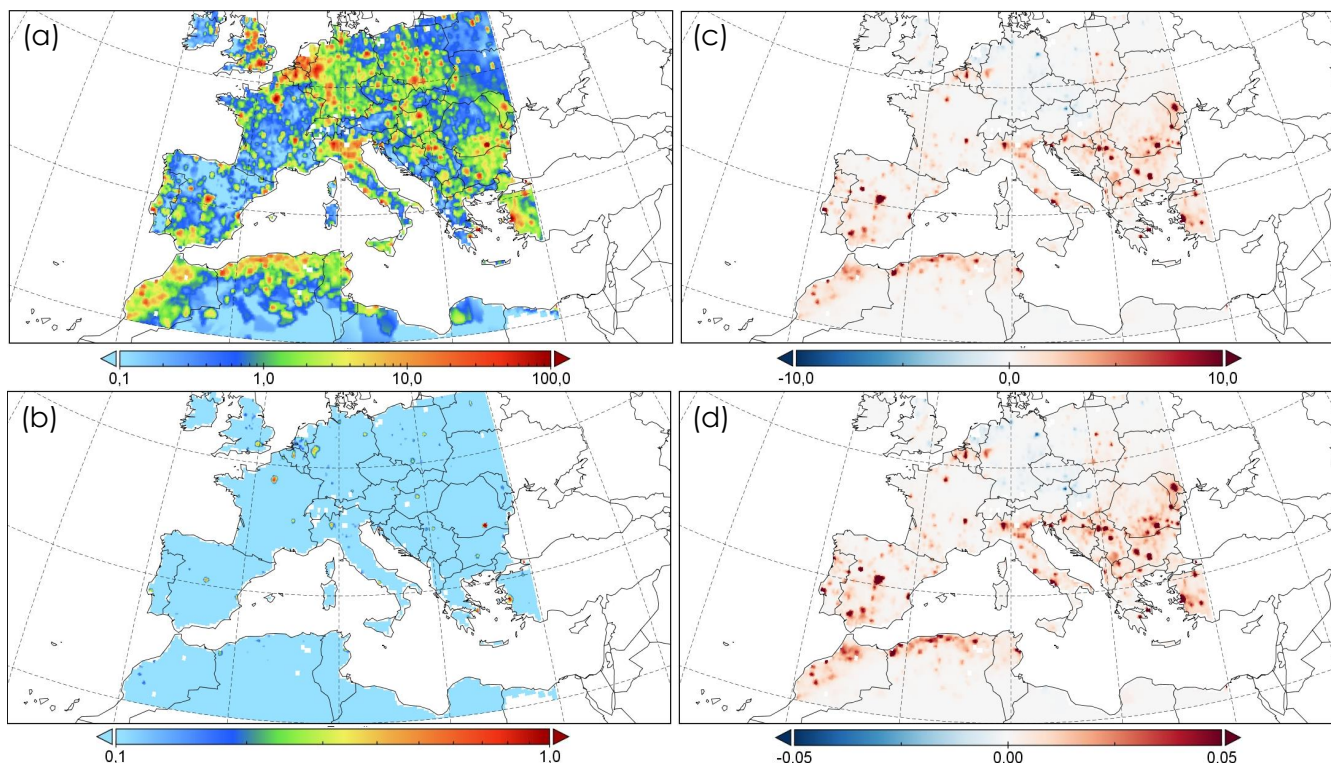
Figure 3. (~~Left columna~~) ~~(Top)~~ Present cases by Cerebrovascular Hospital Admissions (CHA) and (~~bottom~~b) associated costs, in M€. (~~Right columnc~~) Changes projected in CHA cases and (~~top~~d) ~~and~~ changes in costs (~~bottom) (~~M€) under the RCP8.5 scenario (2071-2100).

3.2.3   Congestive Heart Failure (CHF)

CHF, as pointed out in Table 3, involves 117100 cases per year over Europe in the 1996-2015 period, with an associated external cost of 1.3 billion €. Future climate change will increase the cases of CHF by +24% (~~28900~~ 28 900 cases for the entire domain), also increasing the associated costs by the same percentage (increase of 318.3 M€ in external costs for the period 2071-2100).

With respect to the spatial distribution of CHF (Fig. ~~3~~4) within the target area, once again most of the CHF cases are located in Belgium and the Ruhr area; however punctual hotspots appear in the largest European cities (London, Paris, Madrid) with over 1000 cases per year in the entire cities (costs >10 M€), being the highest number found over the city of Bucharest (over 1500 cases per year in all the city, with an associated cost of over 16 M€). In this sense, CHF depends not only on particulate matter, but also on CO levels; hence European megacities are the most important hotspots for this pathology due to their intense traffic, which importantly contributes to CO and NO_x emissions.

CHF cases are widely distributed throughout the territory, with values generally under 10 cases per year and cell. The area with the lowest number of CHF cases for 1996-2015 is the northern Iberian Peninsula. For future projections, an increase of CHF close to 1000 cases in Bulgaria (Sofia and Craiova) and Moldova (Chisinau), with an associated increase in costs up to 11 M€. Once again, a decrease in cases (-36 cases/year cell) and associated costs (variations of -0.4 M€/year cell) is found in central Europe cities such as Vienna or Berlin for the 2071-2100 RCP8.5 scenario.
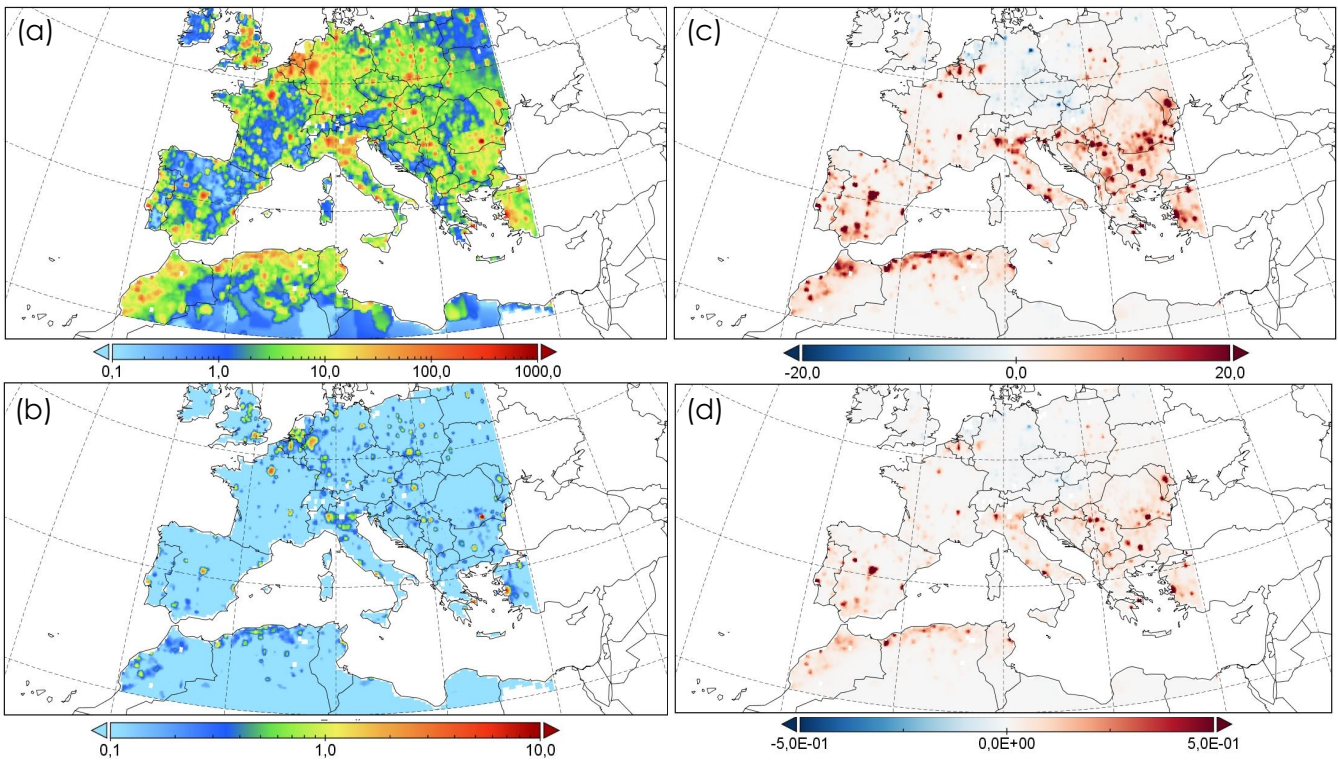
Figure 4. (~~Left column~~a) (~~Top~~) Present cases by Congestive Heart Failure (CHF) and (~~bottom~~b) associated costs, in M€. (~~Right column~~c) Changes projected in CHF cases and (~~top~~d) ~~and~~ changes in costs (~~bottom)~~ (M€) under the RCP8.5 scenario (2071-2100).

3.2.4 Chronic Bronchitis (CB)

Table 3 indicates that CB cases exceed ~~310600~~ 310 600 cases per year in all the target domain for the 1996-2015 period (cost 12 billion €), which will increase by 76800 cases in the RCP8.5 scenario (2071-2100), also increasing the cost by 3.0 billion €in all Europe covered by the simulation domain (+25%).

The CB cases are unevenly distributed over Europe (Fig. ~~4~~5). This pathology is distributed throughout the study area analogously to CHA (Fig. ~~2~~3), since the exposure-response coefficient depends for CB and CHA only on the concentration of particulate matter. Cases exceed 1000 per year (over 50 M€) in cities as Madrid, Paris, Brussels or Bucharest, with a maximum for the latter of 3892 cases for present period study (costs of 150 M€per year). Areas as northern Italy or eastern Europe are largely affected in comparison with other pathologies previously mentioned. For the future scenario, the most affected areas are those reported for the present, with the exception of Chisinau (Moldova), Bucarest (Romania) and Sofia (Bulgaria), where future increases in CB cases may exceed 2600 (increase in external costs of over 100 M€), meanwhile some cities of Germany, Austria or Czech Republic could decrease these pathology cases up to almost 100 (-4 M€/year cell decrease in costs).
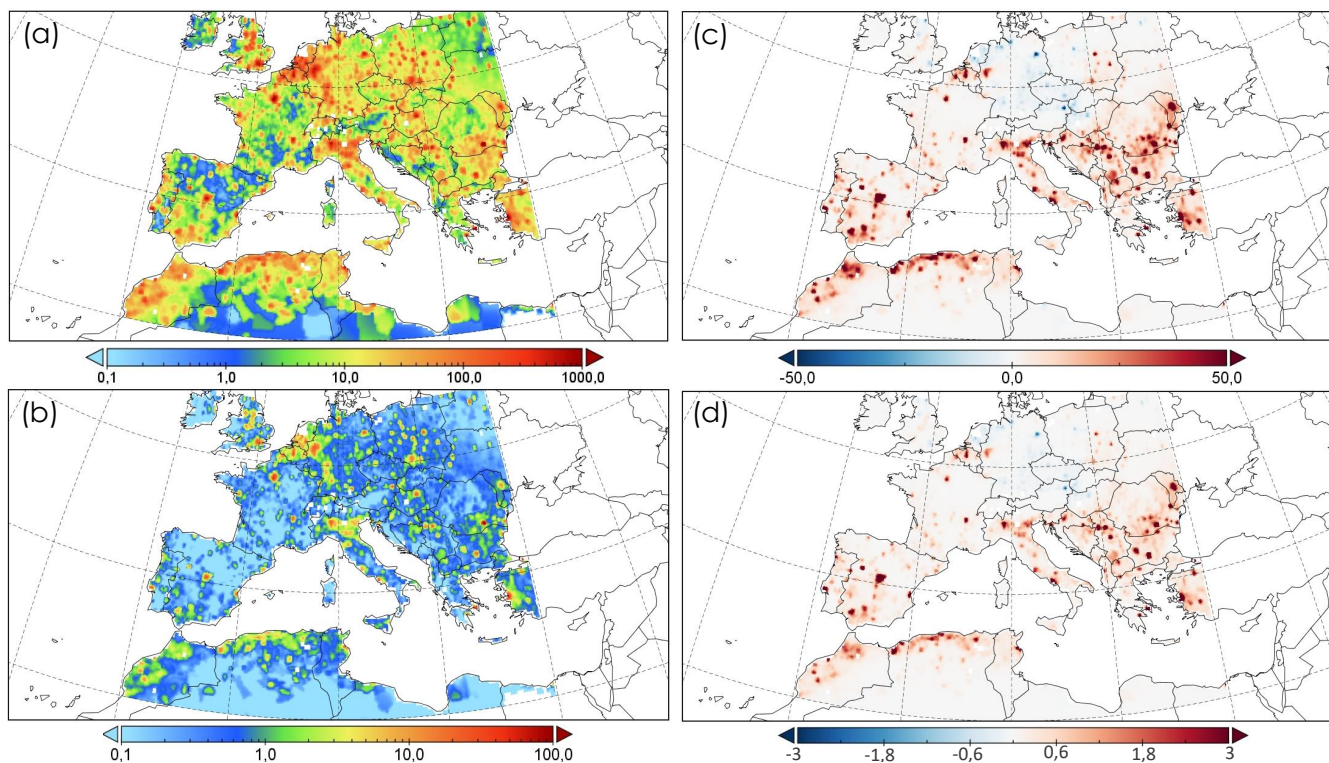
Figure 5. (~~Left columna~~) ~~(Top)~~ Present cases by Chronic Bronquitis (CB) and (~~bottomb~~) associated costs, in M€. (~~Right columnc~~) Changes projected in CB cases and (~~topd~~) ~~and~~ changes in costs (~~bottom) (~~M€) under the RCP8.5 scenario (2071-2100).

3.2.5 Lung Cancer (LC)

Regarding LC, Table 3 estimates 47700 cases per year in Europe for the present climatology, with an associated cost of 765 M€). The projected increase by 2071-2100 reaches +11800 extra cases in the RCP8.5 scenario, with an increase in costs of +189 M€ (+25% of cases and cost increase).

The results for the spatial distribution of LC (Fig. 56) indicate that LC affects principally central and northern Europe, with widespread hotspots throughout the territory. The maxima are found over European megacities (600 cases/year cell in the present climatology; costs over 10 M€). Countries with a widest area with affectations are Belgium and The Netherlands, with an important number of cases in Germany, northern Italy or southern Poland. An increase of over 400 LC cases per year and cell (associated increase in cost of 6.5 M€/year cell) is expected for the 2071-2100 period over southern Europe (Madrid, Rome, Bucarest, Sofia or Belgrade), with decreases of around 10 cases/year cell in cities of eastern Germany and eastern Austria. This decrease in LC (as also shown before for CB) found for more northern areas is strongly related to increases in precipitation found for the RCP8.5 scenario, which may reduce the levels of PM (Jiménez-Guerrero et al., 2013b).
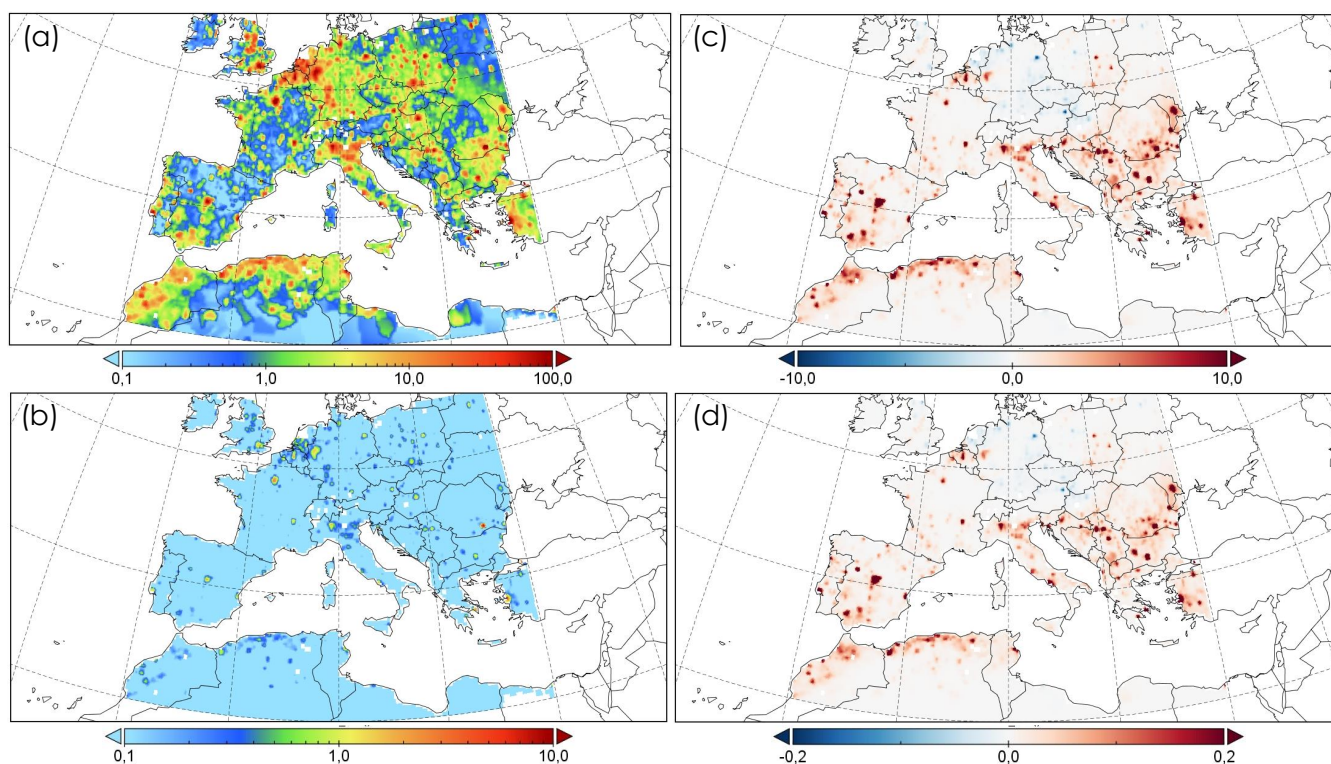

Figure 6. (Left column a) (Top) Present cases by Lung Cancer (LC) and (bottom b) associated costs, in M€. (Right column c) Changes projected in RHA cases and (top d) and changes in costs (bottom) (M€) under the RCP8.5 scenario (2071-2100).

3.2.6 Premature Deaths (PD)

Last, the variable PD covers chronic mortality and acute mortality as defined in ~~(Brandt et al., 2013a)~~Brandt et al. (2013a). Chronic mortality refers to mortality risks associated with long-term exposure, and is quantified in years of life lost (YOLL, depending on PM2.5 concentration for population >30 yr). Last, acute mortality depends on SO_2 levels and SOMO35 (Sum of Ozone Means Over 35 ppb), which is estimated as the sum of means over 35 ppb for the daily maximum 8-hour values of ozone.

Estimates of ~~418700~~ 418 700 cases per year in the target domain are provided in Table 3 for 1996-2015, with a huge associated cost (159 billions €). The projected increase in the RCP8.5 for the years 2071-2100 reaches +~~94900~~ 94 900 extra cases; that is, an increase in costs of over 27 ~~billions~~ billion € (+17% of cases and cost increase).

The dominant pathology over the entire domain (Fig. 6) is PD, especially over central Europe, Belgium, The Netherlands, Germany, Poland, Italy or Bulgaria. These countries have a high number of cases for the whole country. Hotspots are again located over large cities, exceeding 1000 cases/year cell and even reaching ~~4314~~ 4 314 cases in several cities like Paris and London (associated external cost over 700 M€ in these cities). For the future scenario (2071-2100) a clear difference between the northern half and the southern half of study area is depicted. While in southern cities as Madrid (Spain) or eastern Europe cities as Belgrade (Serbia), Bucarest (Romania) or Sofia (Bulgaria) PD may increase up to 2400 cases per year (+450 M€ in several megacities). In cities of countries as Germany (Berlin, Hamburg), France (Paris) or United Kingdom (London, Manchester, Newcastle) a decrease of more than 200 cases per year and cell are projected (reduction of costs over 31.5 M€/year cell).

This variation in premature deaths in southern Europe is mainly caused by the increase of O_3 due to natural emissions, as a consequence of climate change alone and the accumulation in the Mediterranean of long-range transport of tropospheric ozone (and also particulate matter) (Jiménez-Guerrero et al., 2013a, b). Both pollutants are related with cardiorespiratory diseases and premature death (Tagaris et al., 2010; Geels et al., 2015). Conversely, more northern cities such as Berlin or Vienna will benefit from a better air quality on the future projections and a decrease in cases number and, in consequence, on the associated costs. This results from a large decrease in PM levels under an enhanced precipitation scenario (Jacob et al., 2018), as also detailed before for LC.

4 Conclusions

As proposed in the objectives of this contribution, a relationship was established between air pollutant levels and the impacts on several human pathologies. Several reasons lead us to carry this study: (1) the exceedances of the limit values regulated by the European directives or the World Health Organization for several pollutants over some European areas; (2) the scientific literature available showing a clear and increasing relationship between these exceedances and their impacts on human health (e.g. Brandt et al. (2013a, b); Im et al. (2018), whose results furthermore support the conclusiones obtained in this work).

The statistical epidemiological study (corroborated later by the modelling results in this same contribution) identify a clear relationship between pathologies and air pollution by PM, especially in central European countries. The highest coefficient of
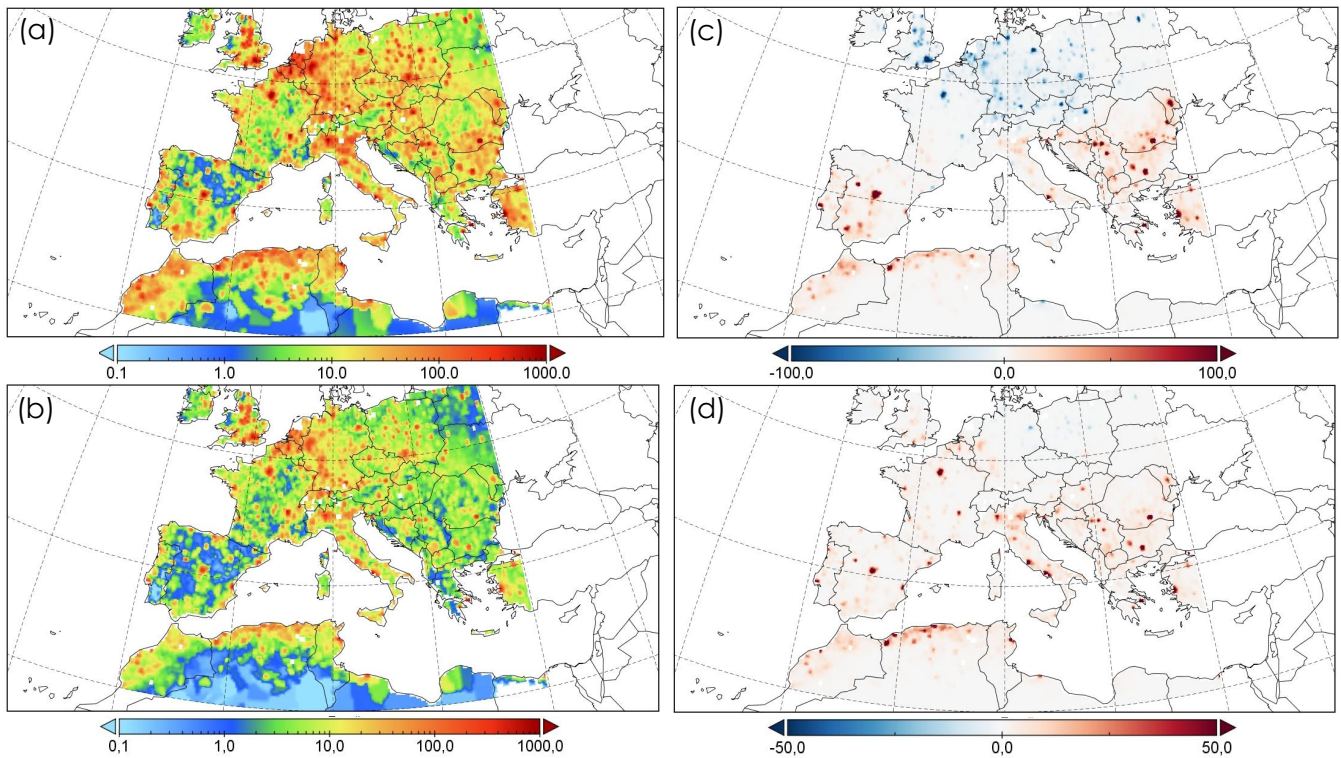
14

Figure 7. (~~Left columna~~) ~~(Top)~~ Present cases of Premature Deaths (PD) and (~~bottom~~b) associated costs, in M€. (~~Right columnc~~) Changes projected in PD and (~~topd~~) ~~and~~ changes in costs (~~bottom)~~ (M€) under the RCP8.5 scenario (2071-2100).

correlation in the epidemiological study are found for total deaths and particulate matter (TD-PM10) in Germany, Slovenia and Czech Republic, and Hungary and Italy for death caused by respiratory diseases (relationship DRD-PM10). The modelling study supports these conclusions, also highlighting that large cities and conurbations (especially in eastern Europe) are to be taken into account in order to analyse the impacts of air pollution on several pathologies and diseases. The pathologies considered importantly impact the societal costs due to the damage produced on population health; and are heterogeneously distributed over Europe and so are the impacts expected due to climate change. Several countries, such as as Moldova or Bulgaria, which are not impacted by present air pollution in the modelled results, will strongly increase the cases and associated costs due to climate change alone.

~~European megacities are important hotspots for health-related issues due to their traffic, which importantly contributes to CO~~ ~~and NO$_x$ emissions. Moreover, SO$_2$ (included in the estimation of RHA and PD)has a role on pathologies since it comes mainly~~ ~~from energy production.In that case, the impacts on eastern countries are higher due to the high sulfur-content fuels in which~~ ~~they base their economy (Colette et al., 2012; Pozzer et al., 2012; Geels et al., 2015). Henceforth, most of hospital admissions~~ ~~are located in European megacities and eastern Europe, with poor air quality levels causing respiratory damage~~Premature deaths are the most important pathology in the study area in terms of costs (158 billion €per year, that will increase by 17% in

15

the future RCP8.5 2071-2100 projection) and cases (418700 cases per year increased by 94900 pear year in the future). This has been already stated by several authors (e.g. Héroux et al. (2015)).

For the future scenario RCP8.5, we can conclude that, overall, all pathologies will increase in southern Europe (especially southeastern Europe) because of the changes projected in PM and O_3 (this latter related to PD, which are expected to increase

5   in RCP8.5 in the aforementioned areas). This scenario will be likely if no mitigation policies for anthropogenic regulatory pollutants are implemented in Europe. On the other hand, northern Europe will benefit from climate change by reducing the levels of air pollution (mainly, PM2.5), as also pointed out by Tagaris et al. (2010). The variation in premature deaths in southern Europe is mainly caused by the increase of O_3 due to natural emissions

Last, as a consequence of climate change alone and the accumulation in the Mediterranean of long-range transport of

10   tropospheric ozone (and also particulate matter) (Jiménez-Guerrero et al., 2013a, b). Both pollutants are related with cardiorespiratory diseases and premature death (Tagaris et al., 2010; Geels et al., 2015). A converse behavior is found for more northern areas, where changes in precipitation may reduce the levels of PM (Jiménez-Guerrero et al., 2013b). For this reason, more northern cities such as Berlin or Vienna will benefit from a better air quality on the future projections and a decrease in cases number and, in consequence, on the associated costs.

15   Premature deaths are the most important pathology in the study area in terms of costs (158 billion per year, that will increase by 17% in the future RCP8.5 2071-2100 projection) and cases (418700 cases per year increased by 94900 pear year in the future). This has been already stated by several authors (e.g. Héroux et al. (2015)).

Last, we can conclude that, overall, all the pathologies included in this study will increase in the future period under climate change RCP8.5 scenario if no mitigation policies for anthropogenic regulatory pollutants are implemented in Europe.

20   Moreover, we starting point for further studies, we should bear in mind that the aging of European population and the increase of city dwellers , variables that in future scenarios have not been taken into account in this study in order just to isolate the effect of climate change alone in the health of European citizens.

References

Analitis, A.,De? Donato, F., Scortichini, M., Lanki, T.;,Basagana, X., Ballester, F., Astrom, C., Paldy, A., Pascal, M., Gasparrini, A., Michelozzi, P., and Katsouyanni, K.: Synergistic Effects of Ambient Temperature and Air Pollution on Health in Europe: Results from the PHASE Project, Int. J. Environ. Res. Public Health, 15(9), 1856, doi:10.3390/ijerph15091856, 2018.

5 Bashkaran, K., Gasparrini, A., Hajat, S., Smeeth, L., and Armstrong, B.: Time series regression studies in environmental epidemiology. Int. J. Epidemiology, 42(4), 1187-1195, https://doi.org/10.1093/ije/dyt092, 2013.

Beelen, R., Raaschou-Nielsen, O., Stafoggia, M., Andersen, Z. J., Weinmayr, G., Hoffmann, B., Wolf, K., Samoli, E., Fischer, P., Nieuwen-huijsen, M., Vineis, P., Xun,W. W., Katsouyanni, K., Dimakopoulou, K., Oudin A., Forsberg B., Modig, L., Havulinna, A. S., Lanki, T., Turunen, A., Oftedal, B., Nystad W., Nafstad, P., De Faire, U., Pedersen, N. L., Östenson, C.-G., Fratiglioni, L, Penell, J., Korek, M., Pershagen, G., Eriksen, K. T., Overvad, K., Ellermann, T., Eeftens, M., Peeters, P. H., Meliefste, K., Wang, M., Bueno-de-Mesquita, B., Sugiri, D., Krämer, U., Heinrich, J., de Hoogh, K., Key, T., Peters, A., Hampel, R., Concin, H., Nagel, G., Ineichen, A., Schaffner, E., Probst-Hensch, N., Künzli, N., Schindler, C., Schikowski, T., Adam, M., Phuleria, H., Vilier, A., Clavel-Chapelon, F., Declercq, C., Grioni, S., Krogh, V., Tsai, M.-Y., Ricceri, F., Sacerdote, C., Galassi, C., Migliore, E., Ranzi, A., Cesaroni, G., Badaloni, C., Forastiere, F., Tamayo, I., Amiano, P., Dorronsoro, M., Katsoulis, M., Trichopoulou, A., Brunekreef, B., and Hoek, G.: Effects of long-term exposure to air pollution on natural-cause mortality: an analysis of 22 European cohorts within the multicentre ESCAPE Project, Lancet, 383, 785-795, https://doi.org/10.1016/S0140-6736(13)62158-3, 2014.

Brandt, J., Silver, J. D., Christensen, J. H., Andersen, M. S., Bønløkke, J. H., Sigsgaard, T., Geels, C., Gross, A., Hansen, A. B., Hansen, K. M., Hedegaard, G. B., Kaas, E., and Frohn, L. M.: Contribution from the ten major emission sectors in Europe and Denmark to the health-cost externalities of air pollution using the EVA model system? An integrated modelling approach, Atmos. Chem. Phys., 13, 7725-7746, https://doi.org/10.5194/acp-13-7725-2013, 2013a.

Brandt, J., Silver, J. D., Christensen, J. H., Andersen, M. S., Bønløkke, J. H., Sigsgaard, T., Geels, C., Gross, A., Hansen, A. B., Hansen, K. M., Hedegaard, G. B., Kaas, E., and Frohn, L. M.: Assessment of past, present and future health-cost externalities of air pollution in Europe and the contribution from international ship traffic using the EVA model system, Atmos. Chem. Phys., 13, 7747-7764, https://doi.org/10.5194/acp-13-7747-2013, 2013b.

25 Brunner, D., Savage, N., Jorba, O., Eder, B., Giordano, L., Badia, A., Balzarini, A., Baró, R., Bianconi, R., Chemel, C., Curci, G., Forkel, R., Jiménez-Guerrero, P., Hirtl, M., Hodzic, A., Honzak, L., Im, U., Knote, C., Makar, P., Manders-Groot, A., van Meijgaard, E., Neal, L., Pérez, J. L., Pirovano, G., José, R. S., Schroder, W., Sokhi, R. S., Syrakov, D., Torian, A., Tuccella, P., Werhahn, J., Wolke, R., Yahya, K., Zabkar, R., Zhang, Y., Hogrefe, C., and Galmarini, S.: Comparative analysis of meteorological performance of coupled chemistry-meteorology models in the context of AQMEII phase 2, Atmos. Environ., 115, 470-498, https://doi.org/10.1016/j.atmosenv.2014.12.032, 2015.

Brook, R. D., Rajagopalan, S., Pope, C., Brook, J. R., Bhatnagar, A., Diez-Roux, A., Holguin, F., Hong, Y., Luepker, R. V., Mittle-man, M. A., Peters, A., Siscovick, D., Smith S. C., Whitsel, L., and Kaufman, J. D.: Particulate Matter Air Pollution and Car-diovascular Disease: An Update to the Scientific Statement from the American Heart Association, Circulation, 121(21), 2331-2378, https://doi.org/10.1161/CIR.0b013e3181dbece1, 2010.

35 Colette, A., Granier, C., Hodnebrog, Ø., Jakobs, H., Maurizi, A., Nyiri, A., Rao, S., Amann, M., Bessagnet, B., D'Angiola, A., Gauss, M., Heyes, C., Klimont, Z., Meleux, F., Memmesheimer, M., Mieville, A., Rouïl, L., Russo, F., Schucht, S., Simpson, D., Stordal, F.,

Tampieri, F., and Vrac, M.: Future air quality in Europe: a multi-model assessment of projected exposure to ozone, Atmos. Chem. Phys., 12, 10613-10630, https://doi.org/10.5194/acp-12-10613-2012, 2012.

Curtis, L., Rea, W., Smith-Willis, P., Fenyves, E., and Pan, Y.: Adverse health effects of outdoor air pollutants, Environ. Int., 32(6), 815-830, https://doi.org/10.1016/j.envint.2006.03.012, 2006.

5   EEA. European Environment Agency. Environment and human health, Joint EEA-JRC report Nr 5. Report EUR 25933 EN, 112 pp. Available through https://www.eea.europa.eu/publications/environment-and-human-health/, May 2019.

Forkel, R., Balzarini, A., Baró, R., Bianconi, R., Curci, G., Jiménez-Guerrero, P., Hirtl, M., Honzak, L., Lorenz, C., Im, U., Pérez, J.L., Pirovano, G., San José, R., Tuccella, P., Werhahn, J., and Zabkar, R.: Analysis of the WRF-Chem contributions to AQMEII phase2 with respect to aerosol radiative feedbacks on meteorology and pollutant distributions, Atmos. Environ., 115, 630-645, 10   https://doi.org/10.1016/j.atmosenv.2014.10.056, 2015.

Geels, C., Andersson, C., Hänninen, O., Lansø, A., Schwarze, P., Skjøth, C., and Brandt, J.: Future premature mortality due to O_3, secondary inorganic aerosols and primary PM in Europe–sensitivity to changes in climate, anthropogenic emissions, population and building stock, Int. J. Env. Res. Public Health, 12(3), 2837-2869, https://doi.org/10.3390/ijerph120302837, 2015.

Giannadaki, D., Lelieveld, J., and Pozzer, A.: The Impact of Fine Particulate Outdoor Air Pollution to Premature Mortality. In: Kara- 15   costas T., Bais A., Nastos P. (eds) Perspectives on Atmospheric Sciences. Springer Atmospheric Sciences. Springer, Cham, 1021-1026, https://doi.org/10.1007/978-3-319-35095-0_146, 2017.

Giorgetta, M., Jungclaus, J., Reick, C., Legutke, S., Brovkin, V., Crueger, T., Esch, M., Fieg, K., Glushak, K., Gayler, V., Haak, H., Holl-weg, H.-D., Kinne, S., Kornblueh, L., Matei, D., Mauritsen, T., Mikolajewicz, U., Müller, W., Notz, D., Raddatz, T., Rast, S., Roeck-ner, E., Salzmann, M., Schmidt, H., Schnur, R., Segschneider, J., Six, K.; Stockhause, M., Wegner, J., Widmann, H., Wieners, K.-H; 20   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., M 25   "uller, W., Notz, D., Raddatz, T., Rast, S., Roeckner, E., Salzmann, M., Schmidt, H., Schnur, 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 CMIP5rcp85 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 30   the WRF model, Atmos. Environ., 39, 6957-6975, https://doi.org/10.1016/j.atmosenv.2005.04.027, 2005.

Héroux, M.-E., Anderson H. R., Atkinson, R., Brunekreef, B., Cohen, A., Forastiere, F., Hurley, F., Katsouyanni, K., Krewski, D., Krzyzanowski, M., Künzli, N., Mills, I., Querol, X., Ostro, B., and Walton, H.: Quantifying the health impacts of ambient air pollutants: recommendations of a WHO/Europe Project, Int. J. Public Health, 60(5), 619-627, https://doi.org/10.1007/s00038-015-0690-y, 2015.

Im, U., Bianconi, R., Solazzo, E., Kioutsioukis, I., Badia, A., Balzarini, A., Baró, R., Bellasio, R., Brunner, D., Chemel, C., Curci, G., 35   Flemming, J., Forkel, R., Giordano, L., Jiménez-Guerrero, P., Hirtl, M., Hodzic, A., Honzak, L., Jorba, O., Knote, C., Kuenen, J. J., Makar, P. A., Manders-Groot, A., Neal, L., Pérez, J. L., Pirovano, G., Pouliot, G., Jose, R. S., Savage, N., Schroder, W., Sokhi, R. S., Syrakov, D., Torian, A., Tuccella, P., Werhahn, J., Wolke, R., Yahya, K., Zabkar, R., Zhang, Y., Zhang, J., Hogrefe, C., and Galmarini, S.:

Evaluation of operational on-line-coupled regional air quality models over Europe and North America in the context of AQMEII phase 2. Part I: Ozone, Atmospheric Environment, 115, 404-420, https://doi.org/10.1016/j.atmosenv.2014.09.042, 2015a.

Im, U., Bianconi, R., Solazzo, E., Kioutsioukis, I., Badia, A., Balzarini, A., Baró, R., Bellasio, R., Brunner, D., Chemel, C., Curci, G., van der Gon, H. D., Flemming, J., Forkel, R., Giordano, L., Jiménez-Guerrero, P., Hirtl, M., Hodzic, A., Honzak, L., Jorba, O., Knote, C., Makar, P. A., Manders-Groot, A., Neal, L., Pérez, J. L., Pirovano, G., Pouliot, G., Jose, R. S., Savage, N., Schroder, W., Sokhi, R. S., Syrakov, D., Torian, A., Tuccella, P., Wang, K., Werhahn, J., Wolke, R., Zabkar, R., Zhang, Y., Zhang, J., Hogrefe, C., and Galmarini, S.: Evaluation of operational online-coupled regional air quality models over Europe and North America in the context of AQMEII phase 2. Part II: Particulate matter, Atmospheric Environment, 115, 421-441, https://doi.org/10.1016/j.atmosenv.2014.08.072, 2015b.

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., Jiménez-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, Atmos. Chem. Phys., 18, 5967-5989, https://doi.org/10.5194/acp-18-5967-2018, 2018.

Jacob, D. J., and Winner, D. A.: Effect of climate change on air quality, Atmos. Environ., 43, 51-63, https://doi.org/10.1016/j.atmosenv.2008.09.051, 2009.

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.

Jerrett, M., Turner, M., Beckerman, B., Pope, C., van Donkelaar, A., Martin, R., Serre, M., Crouse, D., Gapstur, S., Krewski, D., Diver, W. R., Coogan, P., Thurston, G. D., and Burnett, R. T.: Comparing the Health Effects of Ambient Particulate Matter Estimated Using Ground-Based versus Remote Sensing Exposure Estimates. Environ. Health Perspect., 125(4), 552-559, https://doi.org/10.1289/EHP575, 2017.

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 multi physics ensemble, Geophys. Res. Lett., 40, 5764-5769, https://doi.org/10.1002/2013GL057403, 2013.

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(4), 661-671, https://doi.org/10.1007/s10584-013-0944-8, 2013.

Kampa, M., and Castanas, E.: Human health effects of air pollution, Environ. Pol., 151(2), 362-367, https://doi.org/10.1016/j.envpol.2007.06.012, 2008.

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, Atmos. Chem. Phys., 10, 7017-7039, https://doi.org/10.5194/acp-10-7017-2010, 2010.

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(7569), 367-371, https://doi.org/10.1038/nature15371, 2015.

Lobell, D.B., and Field, C.B.: Global scale climate-crop yield relationships and the impacts of recent warming, Environ. Res. Lett., 2, 014002, https://doi.org/10.1088/1748-9326/2/1/014002, 2007.

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., and Meehl, G.A.: The next generation of scenarios for climate change research and assessment, Nature, 463(7282), 747-756, https://doi.org/10.1038/nature08823, 2010.

Palacios-Peña, L., Baró, R., Guerrero-Rascado, J. L., Alados-Arboledas, L., Brunner, D., and Jiménez-Guerrero, P.: Evaluating the representation of aerosol optical properties using an online coupled model over the Iberian Peninsula, Atmos. Chem. Phys., 17, 277-296, https://doi.org/10.5194/acp-17-277-2017, 2017.

Pearce, J. L., Hyer, M., Hyndman, R. J., Loughnan, M., Dennekamp, M., and Nicholls, N.: Exploring the influence of short-term temperature patterns on temperature-related mortality: a case-study of Melbourne, Australia, Environ. Health, 15:107, https://doi.org/10.1186/s12940-016-0193-1, 2016.

Poli, P., Hersbach, H., and Dee, D.P.: ERA-20C: An Atmospheric Reanalysis of the Twentieth Century, J. Clim., 29, 4083-4097, https://doi.org/10.1175/JCLI-D-15-0556.1, 2016.

Pope, C. A., Burnett, R., Krewski, D., Jerrett, M., Shi, Y., Calle, E., and Thun, M.: Cardiovascular mortality and exposure to airborne fine particulate matter and cigarette smoke: shape of the exposure-response relationship, Circulation, 120(11), 941-948, https://doi.org/10.1161/CIRCULATIONAHA.109.857888, 2009.

Pope, C. A., and Dockery, D. W.: Health effects of fine particulate air pollution: lines that connect, J. Air Waste Manag. Assoc., 56, 709-742, https://doi.org/10.1080/10473289.2006.10464485, 2006.

Pozzer, A., Zimmermann, P., Doering, U. M., van Aardenne, J., Tost, H., Dentener, F., Janssens-Maenhout, G., and Lelieveld, J.: Effects of business-as-usual anthropogenic emissions on air quality, Atmos. Chem. Phys., 12, 6915-6937, https://doi.org/10.5194/acp-12-6915-2012, 2012.

Ravishankara, A.R., Dawson, J.P., and Winner, D. A.: New Directions: Adapting air quality management to climate change: A must for planning, Atmos. Environ., 50, 387-389, https://doi.org/10.1016/j.atmosenv.2011.12.048, 2012.

Stieb, D., Shutt, R., Kauri, L., Mason, S., Chen, L., Szyszkowicz, M., Dobbin, A., Rigden, M., Jovic, B., Mulholland, M., Green, M., Liu, L., Pelletier, G., Weichenthal, S., Dales, R., and Luginaah, I.: Cardio-Respiratory Effects of Air Pollution in a Panel Study of Outdoor Physical Activity and Health in Rural Older Adults, J. Occup. Environ. Med., 59(4), 356-364, https://dx.doi.org/10.1097%2FJOM.0000000000000954, 2017.

Tagaris, E., Liao, K., DeLucia, A. J., Deck, L., Amar, P., and Russell, A. G.: Sensitivity of Air Pollution-Induced Premature Mortality to Precursor Emissions under the Influence of Climate Change, Int. J. Environ. Res. Public Health., 7, 2222-2237, https://dx.doi.org/10.3390%2Fijerph7052222, 2010.

Taylor, K. E., Stouffer, R. J., and Meehl, G. A.: An overview of CMIP5 and the experiment design, Bull. Am. Meteorol. Soc. 93, 485-498, https://doi.org/10.1175/BAMS-D-11-00094.1, 2012.

WHO, World Health Organization: Review of evidence on health aspects of air pollution. World Health Organization, REVIHAAP Project Technical Report, Copenhagen, Denmark, 302 pp., available online through http://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.

Zhao, C., Liu, B., Piao, S., Wang, X., Lobell, D., Huang, Y., Huang, M., Yao, Y., Bassu, S., Ciais, P., Durand, J.-L., Elliott, J., Ewert, F., Janssens, I.A., Li, T., Lin, E., Liu, Q., Martre, P., Muller, C., Peng, S., Peñuelas, J., Ruane, A.C., Wallach, D., Wang, T., Wu, D., Liu, Z., Zhu, Y., Zhu, Z., and Asseng, S.: Temperature increase reduces global yields of major crops in four independent estimates, Proceedings of the National Academy of Sciences, 114(35), 9326-9331, https://doi.org/10.1073/pnas.1701762114, 2017.