UNIVERSIDAD DE MURCIA

ESCUELA INTERNACIONAL DE DOCTORADO

Estimation of the impacts of air pollution and climate change on mortality over Europe

Estimación de los impactos de la contaminación atmosférica y el cambio climático en la mortalidad en Europa

Dña. Patricia Tarín Carrasco
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Memoria presentada para optar al Grado de Doctor
por: Patricia Tarín Carrasco

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In those days
when every act become an act of defiance,
hold onto each other.

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Resumen

En la actualidad la población de todo el mundo se encuentra amenazada por los efectos adversos que provocan el cambio climático y la contaminación atmosférica. Hoy en día, hay una más que clara relación entre ambos. Durante las últimas décadas se ha visto el impacto que ambos causan en la sociedad, provocando daños en infraestructuras, en los recursos o en la economía. Más recientemente, estudios muestran como la relación del cambio climático y la contaminación atmosférica tienen efectos adversos en la salud humana en el presente y en el futuro, debido a que la acción del cambio climático provocará un empeoramiento de la calidad del aire en algunas zonas y por consiguiente el bienestar de la población se verá afectado (Burnett et al., 2018; Cohen et al., 2017; Geels et al., 2015; Lelieveld et al., 2015, 2019; Silva et al., 2015). Estos impactos en la salud de la población también repercuten en la economía de la sociedad (Brandt et al., 2013a, 2013b; Im et al., 2018; Tarín-Carrasco et al., 2019).

Numerosas instituciones, como la Organización Mundial de la Salud (OMS), alertan del peligro que supone para la población la exposición a los contaminantes que se encuentran en la atmósfera, ya sea a corto o largo plazo. En 2012 la OMS estimó que cerca de 7 millones de personas mueren cada año en todo el mundo a causa de la exposición a la contaminación. No todos los contaminantes provocan los mismos daños en salud, la exposición a materia particulada (PM) causa especial interés debido a su peligrosidad ya que provoca numerosos impactos en salud humana (Burnett et al., 2014, 2018; Liang et al., 2018; Lelieveld et al., 2019; Silva et al., 2013).

Además de esta estrecha relación con la contaminación atmosférica, el cambio climático también provoca eventos extremos relacionados con el aumento de las temperaturas (Mitchell et al., 2006), como las olas de calor o incendios forestales.

Estos eventos también tienen repercusiones en salud humana, aunque sea de forma indirecta. En el caso de los incendios forestales, como muestra Augusto et al. (2020), las emisiones producidas en los incendios forestales tienen impactos en la salud de la población, ya sea cerca del mismo foco emisor o a kilómetros de distancia a causa de la contaminación transfronteriza. Por lo tanto, estos eventos también representan una amenaza para la población.

La calidad del aire se ha ido deteriorando con los años desde la revolución industrial a causa de la acción antrópica (Schulz et al., 2006), por lo que es primordial apostar por políticas de mitigación en las que se reduzcan las emisiones producidas por sectores contaminantes como el sector industrial, tráfico rodado o el energético. Lelieveld et al. (2015) estimaron que para el año 2050 el número de muertes prematuras causadas por la contaminación atmosférica podría ser el doble si no se toma ninguna acción.

Esta Tesis se centra en el estudio de los impactos del cambio climático y la contaminación atmosférica en el continente europeo ya que es una de las regiones del mundo con mayor sensibilidad al cambio climático (Giorgi, 2006); y en especial en la Cuenca Mediterránea, la cual, en el futuro también se verá afectada por el aumento de la concentración de materia particulada (Colette et al., 2012; Jiménez-Guerrero et al., 2013a).

Por tanto, cada vez resulta más preciso el estudio del impacto del cambio climático en la futura calidad del aire y las repercusiones que ambos tienen en la salud de la población. El uso de la modelización resulta una buena herramienta para poder tener una idea del impacto que el cambio climático puede causar en la calidad del aire (Jerret et al., 2017) y por consiguiente el impacto de esta contaminación en la población de todo el planeta.

Por todo ello, el objetivo principal de esta tesis es estimar el impacto de la contaminación atmosférica y el cambio climático en la salud de la población europea, tanto para el periodo presente (1991-2010) como las diferencias esperadas en el futuro a causa del impacto del cambio climático (2031-2050, RCP8.5). Este estudio se centrará en la estimación de los impactos que los contaminantes tienen en salud humana, principalmente, los efectos provocados por la materia particulada. Esta estimación se realizará a través de distintas metodologías en los distintos capítulos que se presentan y desde distintos enfoques. Este objetivo nos permite comprender el impacto que el cambio climático tiene por sí solo en la población europea. De este objetivo principal surgen una serie de objetivos específicos que se irán desarrollando en los capítulos que se presentan en esta tesis:

- Estudiar los impactos en salud causados por los contaminantes que se encuentran regulados en Europa para el presente y en un escenario futuro que se encuentra bajo la acción del cambio climático.
- Estimar los costes económicos que estos impactos en salud provocan en la sociedad en Europa en el periodo presente y las diferencias esperadas con el periodo futuro.
- Evaluar los efectos indirectos de los eventos extremos provocados por el cambio climático, como los incendios forestales, sobre la salud humana en Portugal durante los meses de verano.
- Buscar la correlación entre el área quemada causada por grandes incendios y PM10 y al mismo tiempo la relación sobre todas las causas de mortalidad y por causas específicas.
- Cuantificar los casos de muerte prematura en distintos escenarios futuros de cambio climático, estudiando la influencia de la dinámica poblacional futura o la apuesta de energías renovables en Europa. Para ello, se estimarán los efectos de un escenario futuro de mitigación donde el 80% de la energía producida proviene de fuentes renovables.

En el Capítulo 2 se evalúan los impactos que la contaminación atmosférica tiene en el periodo presente (1996-2015) y futuro (2071-2100, RCP8.5) en Europa. Se tienen en cuenta distintos contaminantes que se encuentran regulados en la normativa europea. Se estudia el impacto que dichos contaminantes tienen en salud humana causando patologías relacionadas con el sistema cardiovascular o respiratorio, así como muerte prematura. Además, se evalúa el coste económico que estos impactos en salud tienen en la sociedad. En este capítulo, en primer lugar, se hace un estudio epidemiológico que relaciona PM10 con la mortalidad total y las muertes causadas por enfermedades respiratorias, los datos provienen de la Comisión Europea. En segundo lugar, se hace un estudio de modelización mediante WRF-Chem (Weather Research and Forecasting model coupled with Chemistry) junto con la metodología Economic Valuation of Air Pollution (EVA) desarrollada por Brandt et al. (2013a, 2013b). Esta metodología hace uso de una evaluación económica, así como funciones de exposición-respuesta lineales para poder estimar los impactos de salud. En cuanto a los resultados obtenidos en este estudio, las grandes ciudades europeas, Valle del Ruhr y ciudades del este de Europa son las áreas que presentan más casos y costes. Se espera un aumento de ambas variables sur y este del área de estudio en el escenario futuro, mientras que el norte y centro de Europa podrían verse beneficiados de la acción del cambio climático disminuyendo ambas variables. Todas las patologías aumentarán sus casos en el futuro, siendo la muerte prematura la que presenta más casos (418 700 casos por año en el periodo presente y aumentando 94 900 casos más por año en el periodo futuro). Así mismo, los costes aumentarán de 173 billones por año a 204 billones por año para finales del siglo.

Por otro lado, en el Capítulo 3, para la estimación de los casos de mortalidad prematura, a diferencia del Capítulo 2, se hace uso de funciones de exposición-respuesta no-lineales. Además, este estudio se centra únicamente en los impactos que produce PM2.5. Se sigue la metodología desarrollada por Burnett et al. (2018) y Lelieveld et al. (2019). Se estudió la mortalidad producida por distintas causas para el periodo presente (1991-2010) y futuro (2031-2050, RCP8.5). Otra diferencia con el estudio realizado en el Capítulo 2, es que en este caso también se tienen en cuenta para los resultados del escenario futuro los cambios en la dinámica poblacional para el año 2050. Las proyecciones de población futura se obtuvieron de las Naciones Unidas. Se usó el modelo climático/química WRF-Chem bajo el dominio de Euro-CORDEX. Se han estimado 895 000 muertes prematuras anuales para el periodo presente y un aumento del 72% para el periodo futuro (1 540 000 muerte anuales). La principal causa de mortalidad es enfermedad isquémica del corazón (IHD) en ambos periodos. A pesar de la disminución de la población en el futuro, la mortalidad aumentará debido a los cambios en la dinámica poblacional (envejecimiento de la población). Las áreas más afectadas son el centro y este de Europa, mientras que se espera un aumento de los casos de mortalidad en el sur y este de Europa en el escenario futuro.

En el Capítulo 4 se sigue la metodología planteada en el capítulo anterior pero en este caso se estima la mortalidad en un escenario de mitigación futuro, donde el 80% de la producción energética en Europa procede de fuentes renovables. En el escenario presente (1991-2010) se cuenta con 895 000 muertes prematuras, en el escenario futuro (2031-2050, RCP8.5) donde sólo se tiene en cuenta el impacto del cambio climático, el aumento del número de casos de muertes prematuras anuales sería de 0.2% (896 000 casos), mientras que si para ese mismo escenario futuro bajo la acción del cambio climático contáramos con la dinámica poblacional, el aumento sería del 71.96% (1 540 000 casos). Aplicando el escenario de mitigación, el total de muertes anuales aumentaría un 71.67% con respecto al escenario presente (1 480 000 casos). El área más beneficiada de los resultados obtenidos en el escenario de mitigación es el este de Europa.

Por último, en el Capítulo 5 se hace un estudio de los efectos provocados por un evento extremo causado por el cambio climático, los incendios forestales. El sur de Europa es una de las áreas más afectadas por los incendios, y en las últimas décadas Portugal ha sido el país más afectado por estos eventos en área ardida en comparación con el territorio del país. Por esta razón este estudio se centra en la estimación de los impactos en salud causados por las emisiones provocadas por los incendios en Portugal. En este capítulo se estudian los fuegos ocurridos durante los meses en los que suelen tener lugar los fuegos (junio, julio, agosto, septiembre) para el periodo de 2001 a 2016 (últimos años disponibles). Se han seleccionado para el estudio los fuegos de más de 1 000 ha ardidas. Se ha correlacionado esta variable con los datos de PM10 que se obtuvieron de las estaciones de medida de calidad del aire. Los datos de PM10 se obtuvieron de la Agencia Portuguesa de Medioambiente (APA). También se correlacionó estas dos variables con los datos de mortalidad por todas las causas y por causas específicas (circulatorio y respiratorio), los datos de mortalidad se obtuvieron del el Instituto Portugués de Estadística. La correlación de la mortalidad con PM10 y el área ardida se hizo mediante la regresión de Poisson. Se ha encontrado una correlación positiva entre PM10 y área ardida en algunos

NUTS III (regiones) de Portugal, así como una correlación significativa entre área ardida y mortalidad. El norte, centro e interior de Portugal son las áreas más afectadas. Durante el periodo estudiado (2001-2016) más de 2 millones de hectáreas han ardido, de las cuales el 48% se consideran fuegos grandes (>1000 ha.).

Esta tesis muestra la relación entre el cambio climático, la contaminación atmosférica y los distintos impactos que tiene en salud, sobre todo en la mortalidad prematura. El cambio climático tendrá grave repercusiones en la sociedad, empeorando la calidad del aire y la salud de los ciudadanos europeos. Apostar por políticas de mitigación puede ser clave para el bienestar de la población futura. Por ello, futuros trabajos pueden centrarse en el estudio de escenarios en los que se reduzcan emisiones de otros sectores contaminantes como el tráfico o la ganadería intensiva; así como estudiar los impactos de otros contaminantes que también tienen graves repercusiones en la salud como el O_3, el cual se relaciona con las olas de calor, episodios cada vez más extremos debidos a la acción del cambio climático. También se podría centrar el estudio en población sensible a la contaminación como las mujeres embarazadas o los neonatos; o centrar el estudio en enfermedades neurodegenerativas, las cuales también se han relacionado recientemente con la contaminación atmosférica.

Abstract

Nowadays there is a clear link between climate change and air pollution. In addition, numerous studies show that this relation has adverse human health effects (Burnett et al., 2018; Cohen et al., 2017; Geels et al., 2015; Lelieveld et al., 2015, 2019). Not only human health is affected, but also the economy can be modulated by air pollution (Brandt et al., 2013a, 2013b; Im et al., 2018; Tarín-Carrasco et al., 2019). Several institutions, as World Health Organization (WHO), warn about the danger of outdoor air pollution to the population, either short- and long- term exposition. In 2010, WHO estimated that about 7 million people die each year worldwide from exposure to pollution. The exposition to Particulate Matter (PM) has a special interest, since PM provokes important impacts on human health (Burnett et al., 2014, 2018; Liang et al., 2018; Lelieveld et al., 2019; Silva et al., 2013), from premature deaths to cardiovascular diseases.

Extreme events associated to climate change, closely related with air pollution, are expected to increase during the 21st century, including events caused by raising temperatures (Mitchell et al., 2006), as heatwaves or wildfires. Therefore, the study of the impact of climate change on future air quality and the repercussions that both have on the population's health is becoming more and more valuable. Modelling tools can help assessing the impact that climate change can have on air quality (Jerret et al., 2017) and therefore, the impact of air pollution on the population worldwide.

Indirectly, these extreme events also have repercussions on human health. With respect to wildfires, Augusto et al. (2020) show that wildfire emissions have impacts on human health, either near the same source or downwind due to transboundary pollution.

Air pollution has increased during the last decades since the industrial revolution due to the anthropic action (Schulz et al., 2006), so it is essential to establish on

mitigation policies that contribute to improve air quality. In this sense, Lelieveld et al. (2015) estimated that the number of premature deaths due to air pollution could be the double for the year 2050 if no mitigation action is carried out.

Under this umbrella, this thesis is focused on Europe, which is one of the regions on the world with the greatest sensitivity to climate change (Giorgi, 2006); and especially on the Mediterranean Basin, that will be affected under future scenarios by a large increase of particulate matter concentration (Colette et al., 2012; Jiménez-Guerrero et al., 2013a).

Therefore, the main objective of this thesis is to estimate the impact of air pollution and climate change on the health of the European population, both for a present reference period (1991-2010) and for the difference expected on the future scenario under climate change (2031-2050, RCP8.5). This dissertation focuses mainly on the different effects caused by particulate matter. This estimation will be calculated by different methodologies and approaches, that will be deeply described in each chapter. This objective allows us to understand the climate change impact has itself on European population. A series of specific objectives arise from the main objective, that can be summarized as:

- To study the impacts that regulatory pollutants provoke on human health for the present period (1991-2010) over Europe and for a future climate change scenario (RCP8.5, 2031-2050).
- To estimate the economic costs that the aforementioned human health impacts have the European society on the present period and the expected differences with the future period.
- To evaluate the health effects of extreme events, as the wildfires in Portugal that take place during the summer months. In this sense, the correlation between the burned area caused by large fires and PM10 and at the same time the relation with all causes mortality and the specific causes mortality has been sought.
- To quantify the premature deaths on different future climate change scenarios. For that, the influence of the future population dynamics or a

high-renewable energy scenario (80% of the produced energy coming from renewable sources) over Europe have been analysed.

The structure of the PhD Dissertation can be summarized as follows:

Chapter 2 evaluates the impacts on human health and economic costs that air pollution has on the present period (1996-2015) and a future scenario (2071-2100, RCP8.5) over Europe. Different regulated pollutants have been taken into account (e.g. particulate matter, sulphur dioxide, carbon monoxide, tropospheric ozone, nitrogen dioxide). The impact of climate change on some pathologies related with cardiovascular and respiratory system have been studied, as the premature deaths number. Besides, the impact of health on economic costs has been evaluated. First, an epidemiologic study has been conducted in this chapter. PM10 has been related with different pathologies whose data has been obtained from the European Commission. Second, a modelling study have been done through WRF-Chem (Weather Research and Forecasting model coupled with Chemistry) and the methodology Economic Valuation of Air Pollution (EVA) developed by Brandt et al., (2013a, 2013b). This methodology makes use of an economic evaluation, as well as linear exposure-response functions to estimate the health impacts. Regarding the results obtained in this study, the most affected areas, in terms of cases ad costs, are the European large cities, the Ruhr Valley and some European eastern cities. An increase of both variables (pathologies and economic costs) is expected on the south and east of Europe on the future scenario. Conversely, northern and central Europe could benefit of the climate change action decreasing both variables. All the studied pathologies will increase the number of cases on the future scenario, being premature death the most important health problem (418,700 cases per year for the present period and increasing in 94,900 cases per year for the future period). Moreover, costs will increase from 173 billion per year to 204 billion per year by the end of the century.

Chapter 3 goes one step beyond by using non-linear exposure-response functions for the estimation of premature deaths. Moreover, this chapter focuses just on PM2.5 impacts. The methodology developed by Burnett et al. (2018) and Lelieveld et al. (2019) has been followed. The mortality produced by different causes has been studied for the present period (1991-2010) and a future scenario (2031-2050, RCP8.5). Another difference with the study presented in Chapter 2 is that here future population dynamics for the year 2050 have been taken into account. The future population projections have been obtained from United Nations. The climate/chemistry model WRF-Chem under the Euro-CORDEX domain has been used. With respect to the results, 895,000 annual premature deaths have been estimated for the present period and an increase of 72% is expected for the future period (1,540,000 annual deaths). The main cause of premature mortality is Ischemic Heart Disease (IHD) for both periods. Despite population declines in the future, the mortality will increase due to the population dynamics (aging population). The most affected areas are central and eastern Europe, while for the future scenario an increase of mortality cases is expected in southern and eastern Europe.

Chapter 4 follows the methodology contemplated in the previous chapter to estimate premature mortality under a future mitigation scenario where the 80% of the energy production comes from renewable sources. Present scenario (1991-2010) accounts for 895,000 premature deaths. On the other hand, in the future scenario (2031-2050, RCP8.5) where just the climate penalty is considered (constant population), the increase of the annual premature deaths will be +0.2% (896,000 cases). If population dynamics is added to climate penalty, the increase will be noticeable +71.96% (1,540,000 cases). Under the mitigation scenario, the total annual deaths will increase by +71.67% compared with the present scenario (1,480,000), reducing by 60,000 premature deaths the business as usual scenario for the 2031-2050, RCP8.5 simulations. The most benefited area from the results obtained in the mitigation scenario is eastern Europe.

Finally, Chapter 5 covers the effects provoked by an extreme event, studying the wildfires impacts on human health by the air pollution released. Southern Europe is one of the most affected areas by wildfires worldwide. During the last decades, Portugal has been the most affected country for this event in terms of burned area compared with the extension of the country. For this reason, this study is focused on the estimation of the impacts on human health caused by wildfires emissions. In this chapter the fires occurred during summer months (June, July, August and September) for the period 2001 to 2016 (the last years available) have been studied. Fires with more than 1,000 ha burned have been selected. This variable was correlated through different methodologies with PM10 data

which was obtained from the background stations. PM10 data come from *Agência Portuguesa do Ambiente* (APA). Also both variables have been correlated with mortality data, all-causes mortality and cause-specific mortality (circulatory and respiratory). Mortality data was obtained from *Instituto Portugues de Estatística*. The correlation between mortality, PM10 and burned area has been estimated by Poisson regression. A positive correlation between PM10 and burned area in some Portugal NUTS III (regions) have been found, as well as a significant correlation between burned area and mortality. The most affected areas are located in northern, central and inland of Portugal. During the studied period (2001-2016) more than 2 millions of hectares have burned, and 48% of the fires are considered large fires (>1,000ha).

This Dissertation depicts the relation between air pollution and the different impacts that air pollution has on human health, especially on premature deaths. Climate change will have serious repercussions on European society, worsening air quality and the health of European dwellers. Implementing mitigation policies could be the key to the welfare of the future population. Thus, future studies can focus on the study of source contribution scenarios (e.g. traffic or cattle industry). Also, the study of other pollutants (in addition to particulate matter) which have serious impacts on human health, as tropospheric O_3, can be interesting. This pollutant is related with heatwaves, events that will become more intense and frequent due to climate change. Further studies might focus on sensitive population as pregnant women or neonate children; or might cover endpoints as neurodegenerative diseases, which are also recently related to air pollution.

Contents

Chapter 3: Contribution of fine particulate matter to present and future premature mortality over Europe: a non-linear response 43

Chapter 4: Reducing future air pollution-related premature mortality over Europe by mitigating emissions: assessing an 80% renewable energies scenario .. 69

List of Figures

List of Tables

Acronyms

ACCMIP Atmospheric Chemistry and Climate Model Intercomparison Project

APA Agência Portuguesa do Ambiente

BA Burned Area

Benelux Belgium, the Netherlands, and Luxembourg

CB Chronic Bronchitis

CEV Cerebrovascular Disease

CH_4 Methane

CHA Cerebrovascular Hospital Admissions

CHF Congestive Heart Failure

CMIP5 Coupled Model Intercomparison Project, phase 5

CO Carbon monoxide

CO_2 Carbon dioxide

COPD Chronic Obstructive Pulmonary Disease

DRD Deaths caused by Respiratory Diseases

ECF European Climate Foundation

EEA European Environment Agency

EFFIS European Forest Fire Information System

EMEP European Monitoring and Evaluation Programme

ERA Atmospheric Reanalyses

Euro-CORDEX European Domian of Coordinated Regional Climate Downscaling Experiment.

EVA Economic Valuation of Air Pollution

FUT-P2010 Future scenario under Climate Change action (RCP8.5) with population constant at 2010

FUT-P2050 Future scenario under Climate Change action (RCP8.5) with population dynamics projected for the year 2050

GBD Global Burden Disease

GEMM Global Exposure Mortality Model

GHG Greenhouse Gases

GOCART Global Ozone Chemistry Aerosol Radiation and Transport model

ICD International Classification of Diseases

ICNF Instituto da Conservaçao da Natureza e das Florestas

IHD Ischemic Heart Disease

INE Instituto Nacional de Estatística

IPCC Intergovernmental Panel on Climate Change

LC Lung Cancer

LRI Lower Respiratory Infection

MADE Modal Aerosol Dynamics Model for Europe.

MEGAN Model of Emissions of Gases and Aerosols from Nature model

N_2O Nitrous Oxide

NASA National Aeronautics and Space Administration

NCD Non-Communicable Diseases

NO_2 Nitrogen Dioxide

NO_x Nitrogen Oxides

NUTS Nomenclature of Territorial Units for Statistics

O_3 Tropospheric Ozone
OMS Organización Mundial de la Salud

PBL Planetary Boundary Layer

PD Premature Deaths

PESETA II Project Projection of Economic impacts of climate change in Sectors of the European Union based on bottom-up Analysis

PM Particulate Matter

PM10 Particulate Matter with a diameter under 10 μm

PM2.5 Particulate Matter with a diameter lower than 2.5 μm

Pop the exposed population

PORDATA Base de Dados Portugal Contemporâneo

PRE-P2010 Present scenario with population constant at 2010

RACM-KPP Regional Atmospheric Chemistry Mechanism-Kinetic Pre-Processor

RADM2 Regional Acid Deposition Model version 2

RCP2.6 Representative Concentration Pathways 2.6 W/m^2 radiative forcing

RCP4.5 Representative Concentration Pathways 4.5 W/m^2 radiative forcing

RCP6 Representative Concentration Pathways 6 W/m^2 radiative forcing

RCP8.5 Representative Concentration Pathways 8.5 W/m^2 radiative forcing

REN80-P2010 Future scenario under Climate Change action (RCP8.5) with a mitigation scenario in which the 80% of European energy production comes from renewables sources and keep constant the population at 2010

REN80-P2050 Future scenario under Climate Change action (RCP8.5) with a mitigation scenario in which the 80% of European energy production comes from renewables sources and population dynamics projected for the year 2050

REVIHAAP Review of evidence on health aspects of air pollution. WHO Project (2013).

RHA Respiratory Hospital Admissions

RR Risk Ratio

RRTM Rapid Radiative Transfer Model

RRTMG Rapid Radiative Transfer Model

SEDAC SocioEconomic Data and Applications Center of NASA

SLCPs Short-lived climate pollutants

SNAP Selected Nomenclature for Air Pollution - for emission source sectors, sub-sectors and activities

SO_2 Sulfur Dioxide

SOMO35 sum of means over 35 ppb for the daily maximum 8 h values of ozone

SORGAM Secondary Organic Aerosol Model

TD Total deaths

UK United Kingdom

UN United Nations

VOCs Volatile Organic Compounds

WHO World Health Organization

WRF Weather Research and Forecasting

WRF-Chem Weather Research and Forecasting model coupled with Chemistry

y_0 the baseline mortality rate

YOLL Years Of Life Lost

YSU Yonsei University scheme

z refers to the PM2.5 concentration in μg m^{-3}

z_0 is the concentration threshold for PM2.5

Chapter 1

Introduction

1.1 Motivation

Air pollution is closely related to climate change and their impacts on human health and welfare are becoming clearer. Numerous institutions and organizations consider air pollution a hazard to public health, and in 2015 the Global Burden of Diseases Study (GBD) identified air pollution as a leading cause of the global disease burden, especially in countries with low and middle incomes (GBD, 2015). The World Health Organization (WHO) has called air pollution an “invisible killer” and as, according to WHO studies, 9 out of 10 people in the world are exposed to polluted air, almost the entire global population is in danger of this “invisible killer” (WHO, 2018).

In the past few decades, the impact of air pollution on human health has been widely studied and established (Burnett et al., 2018; Geels et al., 2015; Lelieveld et al., 2015, 2019; Silva et al., 2013). The evidence of the impact of air pollution on human health is clear. Numerous pollutants can damage our health. There are several effects of air pollution on human health, from hospital admissions, morbidity and chronic diseases to premature mortality (Brandt et al., 2013a, 2013b; Cohen et al., 2017). City dwellers are more exposed to air pollution because urban areas are hotspots of polluted outdoor environments worldwide (Maitre et al., 2006). In the 2018 World Air Quality Report, the city rankings show Asian locations dominating the highest 100 average PM2.5 levels in 2018, with the top 50 cities located in India, China, Pakistan and Bangladesh; while in Europe, the worst air quality is in Eastern Europe, especially Bosnia & Herzegovina.

Air quality has been getting worse since the Industrial Revolution and will become worse under future climate change scenarios. Climate change can change the characteristics of the composition of the atmosphere (Jacob and Winner, 2009). Climate change itself also has impacts on human health, and will bring increased numbers of extreme events associated with temperature (e.g., heatwaves) (Mitchell et al., 2006). In addition, air pollution impacts health in a form that also involves associated external costs to society (Brand et al., 2013a, 2013b, Im et al., 2018). Given these impacts on human health and the costs to the economy, governments should invest in mitigation policies.

Estimating future mortality due to air pollution and climate change is quite difficult. Modelling approaches seem a good tool to estimate the contribution of climate change to future air quality (Jerret et al., 2017). Through modelling and exposure-response functions it is possible to set up a good methodology for estimating the effects of air pollution, including mortality, on future populations.

This thesis focuses on: (1) the impacts of future air quality, given the effects of climate change on human health; (2) evaluation of the present and future economic costs of air pollution for Europe; (3) estimation of the number of cases of health endpoints and mortality in Europe for different age ranges; and (4) identification of the areas in Europe most affected and vulnerable to climate change action, with proposals for future mitigation scenarios. Using the fully on-line coupled meteorological chemistry model, the Weather Research and Forecasting model coupled with Chemistry (WRF-Chem; Grell et al., 2005), exposure-response functions, statistics functions, and air pollution impacts in Europe were estimated.

1.2 State of the art: climate change, air pollution and human health

Air pollution is a severe environmental worry for city dwellers worldwide due to its close relationship with climate change and to the impacts of both on society and human health. Quantifying the effects of air pollution and climate change on human health is difficult: the toxicity of the pollutants, exposure time to them and health conditions of those affected are variable, and data information on pollution concentrations or ambient temperatures are often not readily available.

Several studies have shown that atmospheric composition has been influenced by anthropogenic emissions (Im et al., 2018; Liang et al., 2018; Palacios-Peña et al., 2019, Ravishankara et al, 2012). Human activity has had an important influence on the increase of pollutant concentrations (Schulz et al., 2006) since the Industrial Revolution. As well as contributing to the increase of pollutants in the atmosphere, the chemistry, transport and deposit of certain pollutants could be modified by climate change (Jacob and Winner, 2009). As a result of this relationship, cases of chronic diseases and premature deaths attributable to air pollution and climate change have increased worldwide in recent years (Cohen et al., 2017; Lelieveld et al., 2015; Silva et al., 2017).

Pollutants have severe impacts not only on human health, but also globally on the earth’s climate and ecosystems. Short-lived climate pollutants (SLCPs) have economic impacts by affecting weather processes and reducing agricultural yields, thus threatening food security. SLCPs can persist in the atmosphere for periods from as short as a few days up to as long as a few decades, and their global warming potential is often much greater than carbon dioxide (CO_2) (WHO, 2020).

Pollutants are also linked with health effects and short-term warming of the planet, so reducing them can have almost immediate health and climate benefits for the populations where air quality is poor (Breath Life 2020).

According to WHO 2018a, meeting the goals of the Paris Agreement could save about a million lives a year worldwide by 2050 through reductions in air pollution alone. The health benefits far outweigh the costs of meeting climate change goals. Investing on "win-win" policies which reduce air pollution would also mean lowering the burden of disease attributable to air pollution, as well as contributing to the short- and long-term mitigation of climate change (WHO, 2020).

1.2.1 Climate change: a threat

Climate change is one of the greatest challenges of the 21st century worldwide because of its impacts on the environment and human health. It threatens human society and its well-being through worse air quality or drinking water, rising sea levels, more frequent and extreme weather events, heatwaves and droughts, forest fires and the increased spread of airborne diseases. While these impacts all have economic repercussions on society in general, the most disadvantaged, vulnerable and poor populations are expected to be disproportionately affected by climate change (WHO 2018a).

Berstein et al., (2007) show that the temperature is increasing worldwide and that this increase is greater at higher northern latitudes, with land regions warming faster than the oceans. A rising sea level is consistent with warming, and the level has been rising at an average rate of 1.8 mm/yr (1.3 - 2.3 mm/yr) since 1961 and at 3.1 mm/yr (2.4 - 3.8 mm/yr) since 1993. This is due to thermal expansion, and melting glaciers, ice caps, and polar ice sheets. Observed decreases in snow and ice extent are also consistent with warming. Satellite data since 1978 show that the annual average Arctic sea ice extent has shrunk by 2.7% (2.1 - 3.3%) per decade, with larger decreases in summer of 7.4% (5.0 - 9.8%) per decade. Precipitation, too, presents extreme patterns from 1900 to 2005, increasing significantly in eastern parts of North and South America, northern Europe and northern and central Asia, but falling in the Sahel, the Mediterranean, southern Africa and parts of southern Asia, while, conversely, the area affected by drought has increased. Over the past 50 years, cold days and nights have become less frequent, and hot days and nights more frequent. Moreover, heat waves have become more frequent over most land areas and the frequency of heavy precipitation events has increased over most areas. Average Northern Hemisphere temperatures in the second half of the 20th century were very likely higher than in any other 50-year period in the past 500 years (*Figure 1.1*).

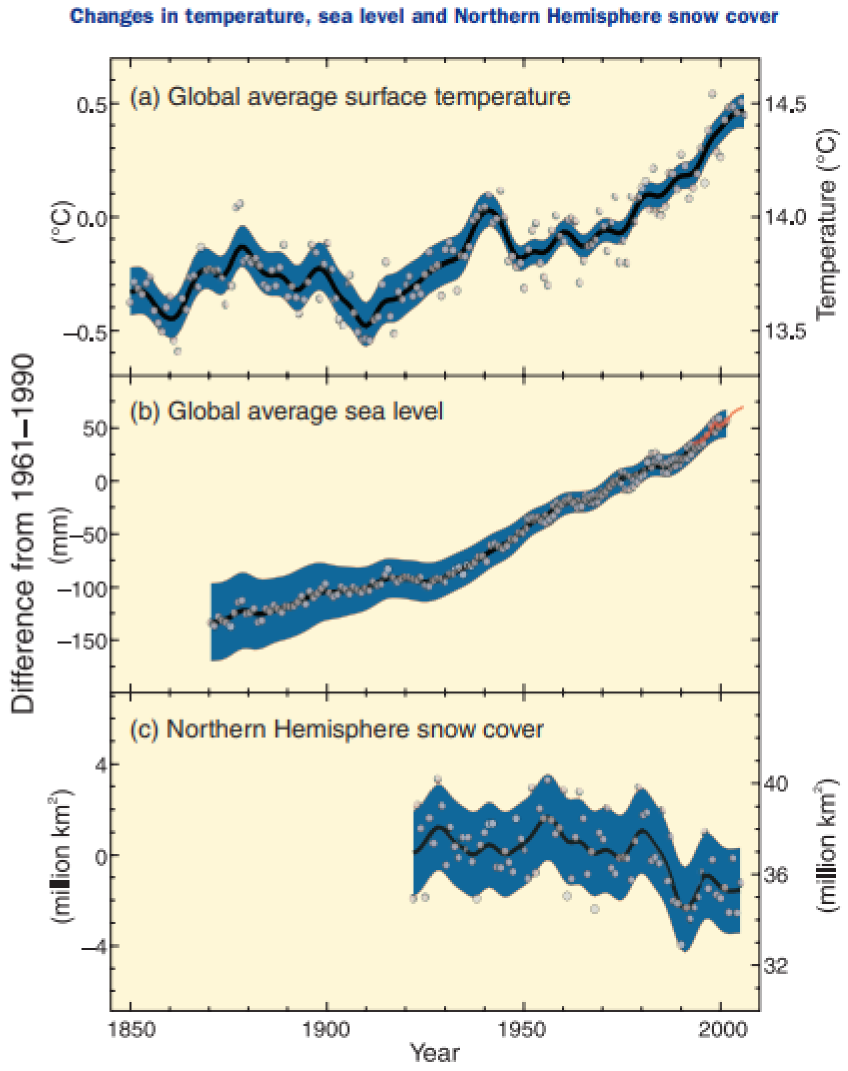

Figure 1.1: *Observed changes in (a) global average surface temperature; (b) global average sea level from tide gauge (blue) and satellite (red) data and (c) Northern Hemisphere snow cover for March-April. All differences are relative to corresponding averages for the period 1961-1990. Smoothed curves represent decadal averaged values while circles show yearly values. Shaded areas are the uncertainty intervals estimated from a comprehensive analysis of known uncertainties (a and b) and from the time series (c). (Bernstein et al., 2007)*

1.2.1.1 Climate change and air pollution relationship

Human activities are destabilizing the Earth's climate and the most direct link is air pollution (WHO, 2018a). Due to transboundary pollution, air pollution affects the whole world (Ravishankara et al., 2012), with some pollutants able to travel long distances and causing health problems on a global scale (Anenberg et al., 2014), with over 90% of the global urban population breathing air that exceeds the WHO's guideline levels for outdoor air pollution (WHO, 2018). Air pollution in cities is rising: in cities monitoring air pollution (Breath Life, 2020), global urban air pollution levels increased by 8% between 2008 and 2013. Outdoor air pollution can originate naturally (e.g., the sea, living organisms, volcanoes, deserts) or anthropogenically (e.g., shipping, motor vehicles, industrial facilities, agriculture, heat and power generation, municipal and agricultural waste incineration, residential cooking, heating, and lighting with polluting fuels). While natural sources contribute substantially to local air pollution, the contribution from human activities is far greater (WHO, 2020). According to Ravishankara, 2012, the problem with natural emissions is that they are difficult to control. Anthropogenic emissions and their precursors are rising in many parts of the world and contributing to the increase of air pollution (Cooper et al., 2014). The main driver of climate change is fossil fuel combustion (for power, transport and industry). The second greatest contributor to global warming is black carbon produced by inefficient combustion in sources such as cook stoves and diesel engines (WHO 2018a). Each emission sector contributes to ambient air pollution in a different way, depending on the region and pollutant, so it is important to propose air pollution control emissions strategies (Silva et al., 2016) which are region-specific. Despite the emissions targets for air pollution that some countries have established, it is difficult for some regions, such as the Mediterranean Basin, to reach their targets due to natural causes (Pozzer et al., 2012).

With regard to the future, the relationship between air quality and climate change becomes clearer: due to the action of climate change, air quality is worsening worldwide, while the most affected area in Europe is the south (Colette et al., 2012; Jiménez-Guerrero et al., 2013a; Ravishankara, 2005). Climate change can modify the concentration and interaction of some pollutants in the atmosphere due to increases in temperature, changes in precipitation or the influence of radiation (Fuzzi et al., 2015; Fiore et al., 2015). Also, the transport and deposition of natural emissions can be altered by climate change (Jacob and Winner, 2009). According to Kirtman et al., (2013), future air quality will be affected not only by climate change, but also by human activity, through future technologies, energy demand, demographic trends, land uses and socioeconomic aspects.

Given the increasingly clear relationship between air pollution and climate change, the future uncertainty of climate change and the lack of awareness of the socioeconomic aspects of the future population, the use of modelling and remote sensing as tools to estimate the relationship between air quality and climate change and their impact would be an optimal way to obtain future projections (Jerrett et al., 2017).

1.2.1.2 Climate change, heatwaves and wildfires

One of the threats to which climate change leads is extreme events, e.g., extreme heat that triggers the increase of heatwaves and wildfires. Extreme heat events are another aspect to consider for a population’s health in a changing climate: short-term exposure to high temperatures can increase the mortality risk (Pearce et al., 2016), heat stress can increase the death rate from heart and respiratory diseases, especially in the elderly (over 65s who are less able to adapt to thermal extremes) (Liss et al, 2017) or vulnerable (people with chronic diseases) (Basu y Ostro, 2008). According to WHO 2018a, in the future, with 1.5°C warming, 350 million more people could be exposed to deadly heat stress by 2050. For this reason, some governments and global organizations have developed emergency response plans to avoid the damage caused by heatwaves (Liss et al., 2017).

Although during the past few decades there has been evidence of the occurrence of heatwaves, none has had as many impacts on human health as the one that occurred in Europe in 2003 (Mitchell et al., 2016). With regard to air pollution, quantifying the mortal and morbid cases due to extreme temperatures is difficult, but the relationship is clear. The risk ratio for each region is different: in Europe, the Mediterranean area is the most affected by high temperatures, with the north of Europe the least affected (Baccini et al., 2008). Also, large urban areas are hotspots for heatwave mortality because of their high population density (Tan et al., 2004).

Extreme temperatures also lead to wildfires, climate change intensifies droughts, changes precipitation patterns and increases temperatures - all are variables that lead to wildfires (Settele et al., 2014). In regions where changed temperature and precipitation patterns are predicted as a result of climate change, the frequency and severity of forest fires are likely to increase, releasing more air pollutants (WHO, 2020). In Europe, the region most affected by burned area is the south, especially Portugal. Despite being a relatively small country, the intensity and number of wildfires there is significant.

With respect to climate change predictions, an increase in the number of droughts, heat waves and dry spells is expected, also impacting currently unaffected areas (Gillett et al., 2004, Turco et al., 2019), and the intensity and number of wildfires will increase due to global warming (Bowman et al., 2017). The PESETA II Project (Projection of Economic impacts of climate change in Sectors of the EU based on bottom-up Analysis) predicts an increase of burned area in southern Europe (Ciscar et al., 2014).

Some studies show the link between wildfires and impacts on human health (Augusto et al., 2020; Liu et al., 2015; Reid et al., 2016). It is difficult to establish the indirect impacts of wildfires on human health due to pollution because there are various factors involved: the pollutant composition of the wildfire (which depends on the type of vegetation), toxicity of the pollutants, size of the fire, distance of the fire from an urban area, and meteorological conditions (e.g., wind, which can transport the pollution long distances, affecting other areas) (Cascio et al., 2018; IPCC, 2007; Lazaridis et al., 2008; Trentmann et al., 2005). The plumes produced by wildfires can include particulate matter (PM), carbon monoxide (CO), methane (CH_4), nitrous oxide (N_2O), nitrogen oxides (NO_x), volatile organic compounds (VOCs), and other secondary pollutants (Cascio, 2018).

It is important to understand the impacts of heatwave and wildfires on the population. For heatwaves, their duration, intensity and time of occurrence, all variables which will increase in the future due to the action of climate change, must be taken into account (Anderson et al., 2011), (Basu y Ostro, 2008; Hajat et al., 2014); while for wildfires, it is vital to create protocols and policies to control their impacts on the population (Rappold et al., 2012).

1.2.1.3 Climate change future scenarios

Estimating future pollution is difficult due to the uncertainty of the mitigation policies of each country. Climate projections are thus an excellent tool to understand the different ways that the future climate might develop given the trend in the past few years of the concentration of greenhouse gases (GHG). A Representative Concentration Pathway (RCP) has been developed by the Intergovernmental Panel on Climate Change (IPCC) to show the different trajectories of a greenhouse gas concentration (not emissions) that present a broad range of climate outcomes based on a literature review and are neither forecasts nor policy recommendations. RCP scenarios include time series of emissions and concentrations of the full suite of greenhouse gases (GHGs), aerosols, and chemically active gases, as well as land use/land cover (Moss et al., 2008). The pathways describe different climate futures, with four RCPs used for climate modelling and defined by their total radiative forcing (cumulative measure of human emissions of GHGs from all sources expressed in watts per square meter (W/m^2), pathway, and level by 2100 (IPCC, 2019, Moss et al., 2010). According to the IPCC (2020), radiative forcing is the change in the net, downward minus upward, radiative flux (expressed in W/m^2) at the tropopause or top of the atmosphere due to a change in an external driver of climate change, such as a change in the concentration of carbon dioxide (CO2) or the output of the sun. The future scenario projections are RCP2.6, RCP4.5, RCP6, and RCP8.5, which are linked with the radiative forcing values in the year 2100, 2.6, 4.5, 6, and 8.5 W/m^2, respectively (*Figure 1.2*).

- RCP2.6 is the stringent pathway. According to the IPCC, this scenario requires carbon dioxide (CO_2) emissions to start declining by 2020 and reach zero by 2100. The emissions of methane (CH_4) should be approximately half by 2020, while those of sulphur dioxide (SO_2) should decline to approximately 10% of the 1980-1990 values (IPCC, 2013). For RCP2.6 the global rise in temperature keeps below 2ºC by 2100. The radiative forcing peaks at approximately 3 W/m^2 before 2100 and then declines (van Vuuren et al., 2011).

- RCP4.5 and RCP6.0 are the intermediate scenarios. Their radiative forcing stabilises at approximately 4.5 W/m^2 and 6.0 W/m^2 after 2100, respectively. While RCP4.5 emissions in RCP4.5 peak around 2040, and then decline, RCP6.0 emissions peak around 2080 (IPCC, 2013).

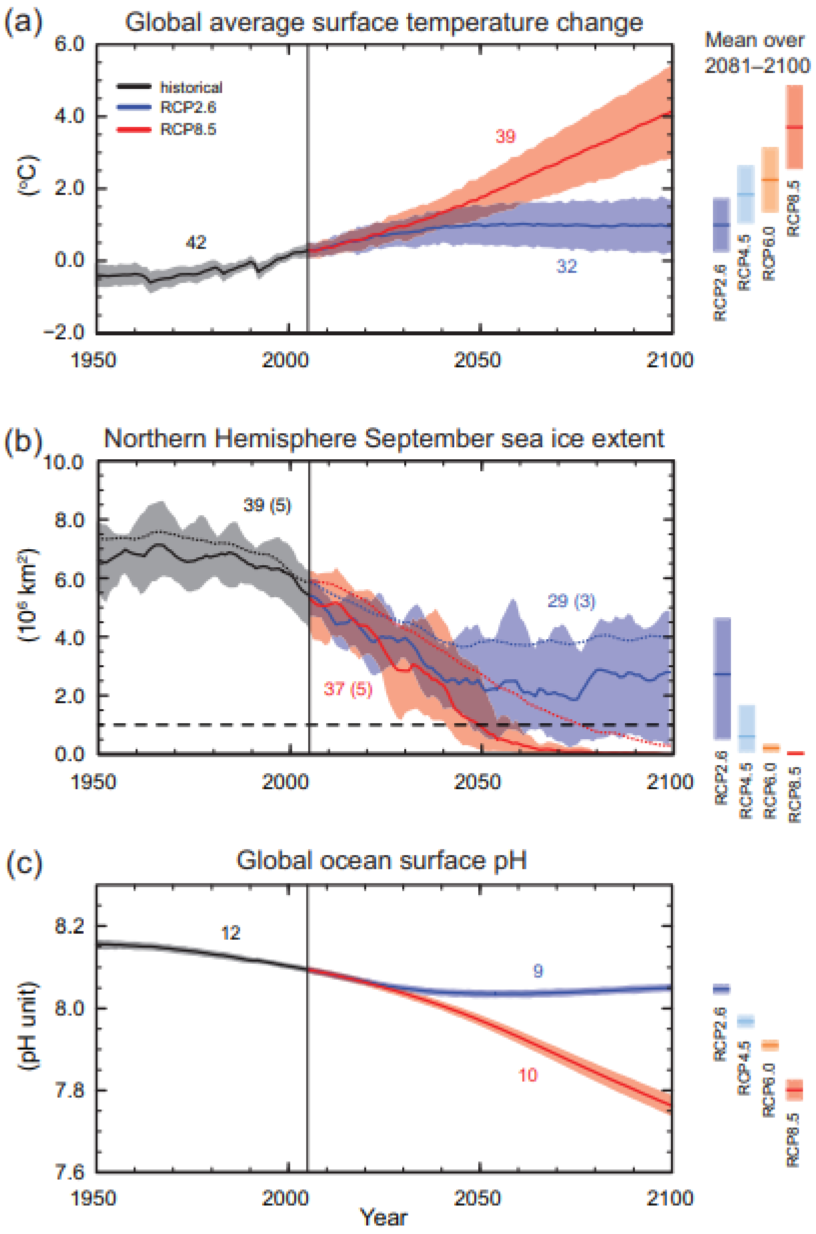

Figure 1.2: *Expected changes in (a) global average surface temperature; (b) Northern Hemisphere September sea ice extent and (c) Global ocean surface pH for the RCP scenarios by 2100. (IPCC, 2013)*

- RCP8.5: this is taken as the basis for the worst-case climate change scenarios. In this scenario, radiative forcing reaches more than 8.5 W/m^2 by 2100 and continues to rise for some years. Moreover, emissions continue to rise throughout the century until 2100 (Riahi et al., 2011). An increase in temperature of between 3.6 and 5.8ºC by 2100 is expected, compared with the pre-industrial era (IPCC, 2013). This scenario was chosen for this study because our objective is to study the impacts of climate change on human health and this scenario provides the upper limit of change signal.

1.2.1.4 Mitigation policies

Exposure to high concentrations of pollutants can constitute a potential risk to city dwellers, so, investing in mitigation policies and reducing the emissions of pollutants can have an immediate positive effect on air quality and consequently on human health ("win-win" policies). If action is not taken by 2050, premature mortality due to air pollution could double (Lelieveld et al., 2015).

Cities are where most cases of morbidity and mortality due to climate change action have been found (Maiter et al., 2006). In addition to being where we can find the greatest numbers of people affected by air pollution, cities are important drivers for climate change due to their emissions and therefore key to reducing carbon emissions, improving health and increasing resilience (WHO, 2018a). According to Breath Life (2020), almost half of the cities monitoring air pollution in high-income countries reduced their air pollution levels by 5% between 2008-2013 and cities in low- and middle-income countries reduced them by almost one third. So, taking action on a local scale can make the difference.

Reducing anthropogenic emissions can reduce the number of deaths caused by climate change and air pollution, according to some authors (Anenberg et al., 2014; Geels et al., 201; Liang et al., 2018). Silva et al., (2016a) and Lelieveld et al., (2019) suggest that taking specific action in some sectors can help reduce some pollutants. Therefore, with stronger action and the imposition of more "sustainable" policies, it is hoped to avoid a drastic deterioration in air quality (Pozzer et al., 2012). In this work, the reduction of the emissions from the energy production sector in the future was studied, comparing a future "business as usual" scenario with a scenario where 80% of energy generation comes from renewable sources.

1.2.2 Air pollution and Human Health

From smog hanging over cities to smoke inside the home, air pollution poses a major threat to health. Nowadays, more and more studies show the relationship between air pollution and human health and the different impacts of air pollution on city dwellers' wellness (Brandt et al., 2013a, 2013b; Burnet et al., 2019; Lelieveld et al., 2015, 2020). It is difficult to know how much air pollution people have been exposed to and the effects of the pollutants on human health. The adverse effects of pollution can differ according to the amount of exposure or type of pollutant, (Kampa and Castanas, et al., 2007), and the complex mechanism by which air pollutants cause these effects is not fully understood (Bernstein, et al., 2004). For this reason, to estimate and quantify the various impacts of air pollution on human health, different methodologies were used by the authors, analysing cohort groups, and estimating the effects with statistical tools (correlations, regressions) and exposure-response functions (linear and non-linear).

1.2.2.1 Pollutant effects

Adverse health consequences of air pollution can occur as a result of short- or long-term exposure, which can be reversible in a short period of time, such as a year (Héroux et al., 2015). Events such as wildfires, when the population is exposed to high concentrations for a short period of time, should be considered a risk for human health (Desikan, 2017; Rappold et al., 2017). Big cities are important hotspots for poor-quality ambient air (Pope et. al., 2002; Mokdad et. al., 2004), which can travel long distances across national borders. Depending on the nature of the pollutants, the length of time they remain in the atmosphere can vary (Lawrence et al., 2007). Pollutants can affect people far away from their source, which is why global cooperation (WHO, 2020c) is important. Each region in the world is affected by a different emissions sector, with land traffic and residential energy use (Lelieveld et al., 2015; Silva et al., 2016a) the main contributors to mortality. Not all countries are similarly affected by air pollution: low- and middle-income countries bear the highest burden, especially in the Western Pacific and South-East Asian regions. In addition, 80% of residents in urban and industrial areas breathe air which exceeds WHO guideline limits (WHO, 2020) and are thus, as McConell et al., (2006) show, at greatest risk.

While several pollutants found in the atmosphere can damage human health, the pollutants with the strongest evidence of health effects are ozone (O_3), nitrogen dioxide (NO_2), sulphur dioxide (SO_2) and, especially, particulate matter (PM) (WHO, 2020c). In order to know the effects of pollution on human health, it is important to know the composition of the pollutants, and the population's health conditions and exposure time to the pollutant (Lelieveld et al., 2015).

According to the WHO (2020), outdoor air pollution is a major cause of death and disease globally, and the effects of air pollution on human health are numerous, ranging from hospital admissions or emergency room visits to premature death. The WHO estimates that 4.2 million premature deaths are due to ambient air pollution. These are due to different endpoint causes, such as lung cancer (LC), acute lower respiratory infection (LRI), stroke, ischaemic heart disease (IHD) or chronic obstructive pulmonary disease (COPD). In this study, the focus was on premature deaths due to Non-Communicable Diseases (or chronic diseases). NCDs tend to be of long duration and are the result of a combination of genetic, physiological, environmental and behavioural factors. According to the WHO (2018), 71% of global deaths are due to NCDs.

Particulate matter (PM), the most worrying pollutant for a population's wellness, is especially well documented (Burnett et al., 2014, 2018; Cohen et al., 2017; Liang et al., 2018; Lelieveld et al., 2019; Silva et al., 2013). The majority of PM concentration comes from natural sources but, since the pre-industrial era, anthropogenic sources have been increasing (Pozzer et al., 2012). These are mainly combustion (engines, solid-fuel, for energy production, industry) and industrial activities (building, mining, the manufacture of cement, ceramic and bricks, and smelting) (WHO, 2020c). The effects that particulate matter can cause depend on various parameters such as the size and surface, number and composition of the particles (Kampa y Castanas, et al., 2007). PM are inhalable and respirable particles capable of penetrating deep into lung passageways and entering the bloodstream, with cardiovascular, cerebrovascular and respiratory impacts (WHO, 2020c). PM10 affects mainly the upper respiratory tract, while fine and ultrafine particles are the greatest risks to health because they can penetrate into the lungs and alveoli, and even into the bloodstream (Kampa y Castanas, et al., 2007). PM10 is composed of sulphate, nitrate, ammonia, sodium chloride, black carbon, mineral dust and water (WHO, 2020c). In Europe, the most affected region is the Mediterranean basin (Pozzer et al., 2012). Studies have shown an increase in morbidity and mortality with gradual increases in PM2.5 and PM10 at ambient levels (Anderson et al., 2012; Bernstein, et al., 2004; Johnston et al., 2012). In addition, the review of evidence on health aspects of air pollution (REVIHAAP) Project (2013) shows that long-term exposure can provoke chronic diseases such as atherosclerosis, diabetes or neurodevelopmental problems, as well as adverse effects on birth outcomes or childhood diseases. PM2.5 is particularly important for public health because of its dangerousness, and for this reason this work has focused mainly on its impacts on human health. The fine particles can damage different organs, such as the lungs, heart or brain, can lead to premature death, and can cause damage even in small concentrations (Beelen et al., 2014).

Together with PM, ground-level ozone (O_3) is a major pollutants influencing the health of worldwide population. Tropospheric ozone is not directly emitted to the atmosphere, but produced when carbon monoxide (CO), methane, or other volatile organic compounds (VOCs) are oxidized in the presence of nitrogen oxides (NO_x) and sunlight (WHO, 2020c). Tropospheric ozone can travel to other areas and has a half-life of a few weeks (Pozzer et al., 2012). Like PM, the highest concentrations of O_3 are located in the Mediterranean region (Colette et al., 2012). Ozone is a major component of photochemical smog and a key health risk linked to breathing problems, asthma, reduced lung function and respiratory diseases (WHO, 2020c). Short-term exposure to this pollutant is also related to respiratory morbidity and mortality (Bell et al., 2014; Stieb et al., 2009), while long-term exposure has been associated with premature mortality (Jerrett et al.,2009).

Gaseous pollutants like NO_x or SO_2, on the other hand, may enter the organism by inhalation, mainly affecting the respiratory system (Bernstein, et al., 2004; Kampa and Castanas, 2007), with increased symptoms of bronchitis and asthma, respiratory infections and reduced lung function and growth, as well as irritation of the eyes in the case of SO_2, increased hospital admissions and visits to emergency rooms, and premature mortality and morbidity from cardiovascular and respiratory diseases (WHO, 2020c). Neither pollutant travels in the atmosphere because they are short-lived, and in Europe the hotspots of these pollutants are located in cities (Colette et al., 2012; Pozzer et al., 2012). NO_2 is emitted by power generation, industrial and traffic sources, while SO_2 is primarily produced by the burning of fossil fuels and the smelting of mineral ores that contain sulphur (WHO, 2020c).

Finally, carbon monoxide (CO) is a gas which at high levels can impair the amount of oxygen transported in the bloodstream to critical organs (WHO, 2020c). It is homogeneously distributed around the world due to its lifetime (several months) (Pozzer et al., 2012). The main sources of ambient CO include motor vehicles and machinery that burns fossil fuels (WHO, 2020c).

1.2.2.2 Exposure-response functions

Given the difficulty in assessing the repercussions of air pollution on human health and society, more and more studies are using exposure-response functions. These functions combine atmospheric science, epidemiology, public health policies and economics. To estimate the effects of the pollutants on human health, cohort studies are evaluated. Cohort studies compare one or more samples and are followed for a period of time, during which the samples are exposed to a risk factor as the study is conducted, the outcome from the participants in each cohort is measured, and relationships with specific characteristics are determined. Cohort studies are particularly advantageous for examining rare exposures and can examine multiple outcomes simultaneously. The disadvantages include the need for a large sample size and the potentially long follow-up duration of the study design, resulting in a costly endeavour (Song and Chung, 2010).

It is important to calculate the Risk Ratio (RR) of the relationship between the pollutants and the exposed population to create mitigation plans for all, especially the sensitive population. According to the WHO, sensitive groups to air pollution are children, elderly people (>65 years old), pregnant and nursing women and people with chronic diseases.

Finally, in this study, linear and non-linear exposure-response functions were used. The differences between them can be observed in *Figure 1.3*. While in the linear function the rate of change is constant, the non-linear function has a threshold value from which, due to greater exposure to the pollutant, there are no adverse effects.

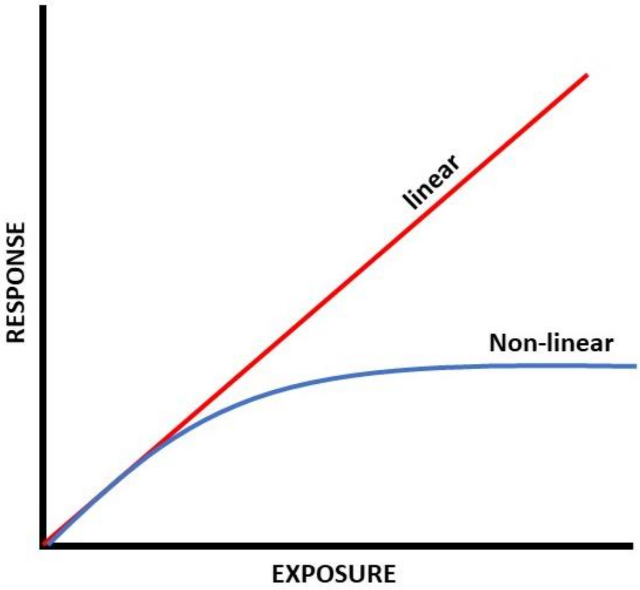

Figure 1.3: *Linear vs. Non-Linear exposure-response functions*

1.2.2.3 European Directive for air quality

In Europe, the air quality is legislated for by European Directive 2008/50/EC on ambient air quality and cleaner air for Europe. This Directive aims to incorporate five previous European Directives in air quality in order to simplify and facilitate its execution.

The objectives of 2008/50/EC European Directive are to establish a series of measures to avoid, prevent or reduce the harmful effects of pollutants on human health and the environment as a whole; in addition to keeping citizens informed about air quality, and maintaining air quality and improving it if necessary. Additionally, it aims to promote cooperation between Member States to avoid cross-border pollution. In the case of non-compliance with the established limits, Member States will establish the relevant sanctions for the infringement and take all necessary measures to ensure they are applied.

Table 1.1: *Limit values for the protection of human health in Annex XI and XIV for 2008/50/EC*

Average Period	Limit value	Margin of tolerance
Sulphur dioxide (SO_2)		
One hour	350 μg m^{-3}, not to be exceeded more than 24 times a calendar year	150 μg m^{-3} (43 %)
One day	125 μg m^{-3}, not to be exceeded more than 3 times a calendar year	None
Nitrogen dioxide (NO_2)		
One hour	200 μg m^{-3}, not to be exceeded more than 18 times a calendar year	50% on 19 July 1999, decreasing on 1 January 2001 and every 12 months thereafter by equal annual percentages to reach 0% by 1 January 2010
Calendar year	40 μg m^{-3}	50% on 19 July 1999, decreasing on 1 January 2001 and every 12 months thereafter by equal annual percentages to reach 0% by 1 January 2010
Carbon monoxide (CO)		
maximum daily eight hour mean	10 mg m^{-3}	60%
PM10		
One day	50 μg m^{-3}, not to be exceeded more than 35 times a calendar year	50%
Calendar year	40 μg m^{-3}	20%
PM2.5		
Calendar year	25 μg m^{-3}	20% on 11 June 2008, decreasing on the next 1 January and every 12 months thereafter by equal annual percentages to reach 0% by 1 January 2015

The limit values established by the European Commission for the protection of human health appear in Annex XI of this Directive, with the limit value for PM2.5 in Annex XIV. (*Table 1.1*). Information and alert thresholds for SO_2, NO_2 and O_3 are in Annex XII (*Table 1.2*).

Table 1.2: *Information and alert thresholds for SO_2, NO_2 and O_3. 2008/50/EC Annex XII*

Sulphur dioxide (SO_2)		500 µg m^{-3}
Nitrogen dioxide (NO_2)		400 µg m^{-3}
O_3	Information	180 µg m^{-3}
	Alert	240 µg m^{-3}

To control emissions, the WHO establishes the limits that countries must comply with and not exceed (Gurjar et., al 2008). The WHO Air quality guidelines (2005) offer global guidance on thresholds and limits for key air pollutants that pose health risks and indicate that by reducing particulate matter (PM10) pollution from 70 to 20 µg m^{-3}, air pollution-related deaths can be reduced by around 15%.

Table 1.3: *WHO pollutant limit values for human health*

Pollutant	Period	µg m^{-3}
PM2.5	1 year	10
	24 hours (99th percentile)	25
PM10	1 year	20
	24 hours (99th percentile)	50
Ozone (O_3)	8 hours, daily maximum	100
Nitrogen dioxide (NO_2)	1 year	40
	1 hour	200
Sulphur dioxide (SO_2)	24 hours	20
	10 min	500

1.3 Objectives

The main objective of this thesis is to estimate the impacts of air pollution and climate change on the European population for the present period (1991-2010) and the future under climate change action (2031-2050, RCP8.5). This objective allows us better understand the effects that climate change alone will have on the population, as well as other factors that could contribute to future health impacts (population dynamics).

In order to achieve this objective, modelling, statistical tools and exposure-response functions were used to estimate the impacts of the pollutants on human health and the economic costs. According to this main target, several specific objectives are derived, as described below:

1. To study the health problems caused by regulatory pollutants in the European population for the present (1991-2010) and a future scenario under climate change action (RCP8.5, 2031-2050).
    - To find the correlation between the concentration of particles with a diameter under 10 µm (PM10) obtained in pollutant-measuring urban stations and respiratory diseases and total deaths, using epidemiological data.
    - To estimate the impact of air pollution on the increase of cases of Non-Communicable Diseases and hospital admissions with data from a regional chemistry-climate model (WRF-Chem).
    - To calculate the premature mortality due to fine particulate matter (PM2.5) due to different endpoints and the age range most affected by air pollution.
    - To isolate the effect of climate change on future air quality and the mortality rate; and to observe the effect of climate change and population dynamics on future mortality.
    - To identify which regions in Europe are most vulnerable to the impacts of air pollution on human health.
    - To compare the sensitivity of the mortality, estimate with two different non-linear methodologies (GEMM and GBD).
    - To contrast the result obtained through linear and non-linear exposure-response functions.
2. To evaluate the economic costs associated with the health problems caused by air pollution in Europe.
    - To appraise the associated costs of several pathologies for the present climate (1991-2010) and the differences with the future climate situation (RCP8.5, 2031-2050).
3. To assess the indirect effects of extreme events caused by climate change such as wildfires on human health in Portugal during the summer months.

  - To describe the correlation between burned area caused by large fires and PM10 and the areas most affected by wildfires.
  - To find the indirect effects of wildfires on natural and cause-specific mortalities through PM10 concentrations.

4. To estimate the future effects of climate change and air pollution on the health and welfare of residents in a future mitigation scenario (RCP8.5 scenario modified with renewables, 2031-2050).
   - To quantify the effects of implementing renewables energies on the mortality of those living in Europe. A future mitigation scenario where 80% of energy production comes from renewable sources.
   - To calculate the difference between present scenario and future climate+mitigation scenario and the difference between two future scenarios (1) climate change action and (2) climate change action+mitigation

The objectives proposed in this thesis allow us to understand the dangers that climate change and air pollution represent for human health and welfare, especially in Europe, on which this study is focused. In addition, the importance of taking action and investing in mitigation policies.

1.4 Scope and structure

As previously stated, the main objective of this thesis is the estimation of the impacts of air pollution and climate change on the European population for the present period (1991-2010) and the future under climate change action (2031-2050, RCP8.5). This task is studied throughout all the chapters in order to achieve the specific objectives.

In chapter two, the effects of certain pollutants on the increase in the number of cases of diseases related to air pollution and hospital admissions were estimated, and the economic costs of these impacts evaluated. The estimates were made using correlations and linear exposure-response functions, following EVA methodology (Brandt et al., 2013a, 2013b).

Chapter three showed premature mortality in Europe due to fine particulate matter (PM2.5), the most sensitive age range to the impact of this pollutant on human health, and the most vulnerable regions to PM2.5 for the present and future scenarios under climate change action (RCP8.5, 2031-2050). Also studied were the effects of population dynamics, analysing and comparing the impact of climate change and the impact of climate change and population dynamics (in the future period. The estimates were made following the methodology proposed by Burnett et al., 2018, GEMM and comparing the results obtained through GBD methodology (Burnett et al., 2015), using non-linear exposure-response functions.

In chapter four, a mitigation future scenario was analysed. A scenario where 80% of energy production is obtained from renewable energies was contemplated, following GEMM (Burnett et al., 2018) methodology, as in chapter three. Future premature mortality in the “business as usual” and mitigation scenarios was compared. The effect of renewable energies on air pollution and, indirectly, the decrease in mortality was observed in this section.

Finally, through Pearson and Poisson correlations, an example of an extreme event caused by climate change was studied. The effect of big fires on air pollution (PM10 concentration) and indirectly on human health was correlated in chapter five. The domain used in this case was Portugal.

Chapter 2

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

Air pollution has important implications for 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 estimate the difference in the costs associated with these health impacts on the European population. For this, air quality data from the regional chemistry–climate modelling system of the Weather Research and Forecasting (WRF) model coupled with Chemistry (WRF-Chem) are used, together with some epidemiological information from the European Commission. The methodology considered relies on the Economic Valuation of Air Pollution (EVA) exposure–response functions and economic valuations (Brandt et al., 2013a, b). Several hypotheses 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 the whole of 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 EUR 173 billion per year to over EUR 204 billion per year at the end of the present century. Premature deaths are the most important problem in the target area in terms of costs (EUR 158 billion per year, increasing by 17% in the future RCP8.5 2071–2100 projection) and cases (418 700 cases per year, increasing by 94 900 cases per year in the future). The most affected areas are European megacities, the Ruhr Valley and several cities in eastern Europe (e.g. Chișinău, Bucharest). For the RCP8.5 scenario, cases and costs will increase over southern and eastern Europe, while central and northern Europe could benefit from climate change variations (decreasing both cases and costs for the studied pathologies).

2.1 Introduction

Currently, 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 premature deaths were caused by exposure to air pollution worldwide (WHO, 2013). In addition, indirectly, air pollution has external costs to society related to damage 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 being reached in southern Europe not only because of anthropic emissions but also because of natural causes (Pozzer et al., 2012), the Mediterranean Basin being the most affected area in terms of increases in air pollution in present and future climate scenarios (Colette et al., 2012; Jiménez-Guerrero et al., 2013a).

Quantifying premature deaths 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 the pollutants' composition, exposure time and the health condition of inhabitants. Lifestyle habits must be considered as well: for instance, Stieb et al. (2017) recommended reducing exposure time and physical activity outdoors under episodes of high concentrations of air pollutants. Moreover, the diverse combination of air pollutants can have additive or synergistic 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 exposure and mortality risk. Therefore, heat extreme events are another aspect to 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 µm (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 deaths. The most important pollutant for the mortality is PM, with a significant decrease in 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 lungs or even pulmonary alveoli (Pope and Dockery, 2006). They cause cardiorespiratory symptoms and illnesses, increased asthma cases, heart attacks, strokes, and even premature deaths (Tagaris et al., 2010). Fine particles can cause damage, even in small concentrations (Beelen et al., 2014). Giannadaki et al. (2017) estimated premature deaths caused by PM2.5 to be 3.15 million per 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 enter the organism by inhalation and affect the 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 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 are calculated to be 414 000 and EUR 300 billion, respectively.

In addition, climate change alone may affect the concentration of these gaseous pollutants and particles through modifications in chemistry in the 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 in air pollution and to obtain future projections of air quality (Jerrett et al., 2017).

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

Henceforth, this study focuses on the analysis of population health problems caused by regulatory pollutants in Europe and on their associated costs. First, the methodology followed aims to find the correlation (if any) between particles with a diameter under 10 µm (PM10) and total deaths and deaths caused by respiratory diseases over Europe 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).

2.2 Methodology

2.2.1 Epidemiological study for present-day climate situation

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 the 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, last access: 10 October 2018) corresponding to the years 2001–2012. Total deaths (TD) and deaths caused by respiratory diseases (DRD) have been analysed. The objective is to find 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 were available from 1994, the targeted period begins in 2001 due to the availability of PM10 data. As in 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 of the different years of entry into the European Union. Taking into account the data availability, the countries selected for the epidemiology analysis were Austria, Belgium, Bulgaria, the Czech Republic, Denmark, Estonia, Finland, France, Germany, Hungary, Iceland, Ireland, Italy, Luxembourg, the Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland and the United Kingdom.

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 ensure their significance at 95% confidence ($p < 0.05$).

2.2.2 Regional chemistry–climate simulations

In addition, air quality model data are 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 period 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 Pathways (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 was the Weather Research and Forecasting (WRF) model coupled with Chemistry (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. A total of 33 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 ERA-20C 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 in 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 includes the following options: the RADM2 chemical mechanism, the MADE/SORGAM aerosol module including some aqueous reactions, the Fast-J photolysis scheme, RRTMG shortwave and longwave radiation schemes and the Yonsei University (YSU) PBL scheme 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 the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP; Lamarque et al., 2010) are assumed. That allows the possible impacts to be anticipated if no mitigation strategies for regulatory pollutants are carried out and the climate penalty on air quality levels to be characterized. Natural emissions depend on climate conditions and therefore vary in present and future simulations. Hence, the effects of climate change on air pollution follow the methodology explained in Jiménez-Guerrero et al. (2013b), excluding possible changes in vegetation or land use.

2.2.3 Present and future impacts of air quality on pathologies

The impact of air quality on the following pathologies is investigated 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 last-mentioned pathology is related both to acute mortality and chronic mortality as defined in Brandt et al. (2013a, b).

For this, gridded population data were obtained from the SocioEconomic Data and Applications Center (SEDAC) of NASA (http://sedac.ciesin.columbia.edu, last access: 20 August 2018) 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 was used, based on counts consistent with national censuses and population registers. The population by cell is shown in *Figure 2.1*. For the future scenario, the population has been kept constant in order to have an educated guess of the possible impacts due only to changes in air quality.

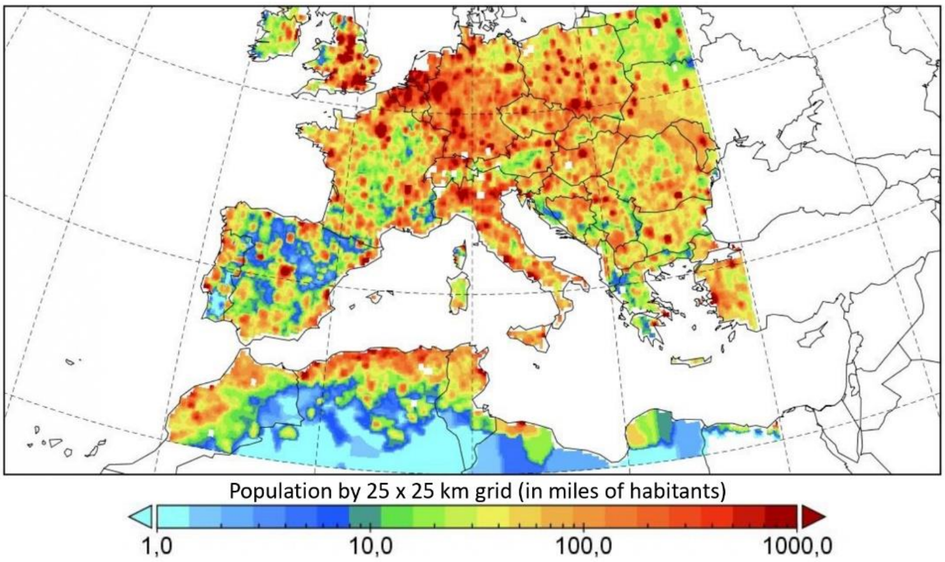

Figure 2.1: *Population in each grid cell (in thousands of habitants) (SEDAC population dataset for 2005)*

Table 2.1: *Pathology, exposure–response coefficients and economic valuation, taken from Brandt et al. (2013a). YOLL represents years of life lost. SOMO35 represents the sum of means over 35 ppb.*

Pathology	Exposure-response coefficient	Valuation
Respiratory Hosp. Adm. (RHA)	3.46×10^{-6} cases/µg m^{-3} PM + 2.04×10^{-6} cases/µg m^{-3} SO_2	7931 €/case
Cerebrovascular Hosp. Adm. (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 +5.64×10^{-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} + 7.85×10^{-6} cases/µg m^{-3} SO_2 + 1.138×10^{-3} YOLL/µg m^{-3} (>30 yr)	2111888 €/case 77199 €/YOLL

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 (taking the value of euros from the year 2006 as a basis) 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 2.1.*

2.3 Results and discussion

2.3.1 Statistical epidemiological study for the present situation

In the following section results from Eurostat data have been analysed. After detrending the data and calculating the anomalies for total deaths (TD), deaths by respiratory diseases (DRD) and PM10, correlations for each country between mortality and particles have been established. The results obtained are shown in *Table 2.2*; bold values indicate correlations significant at the 95% confidence interval ($p < 0.05$). Countries such as Germany, Hungary, Italy and Slovenia present a clear relation between such pollutants and both TD and DRD, with a high correlation in the anomaly series and high statistical significance. Meanwhile, countries such as the Czech Republic, Estonia and Switzerland present a notable statistically 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 significantly low correlation (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 timescale of the data series or the limited number of years with data available hampering the significance of the series.

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

Table 2.2: *Correlation data between total deaths (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

2.3.2 Present and future scenario study on the pathologies and costs related to air pollution

This section discusses the results found for case distribution (number of people) with different pathologies caused by several air pollutants for a present climate situation (1996–2015) and the differences with a future RCP8.5 scenario (2071–2100). A summary of the global cases and associated costs is shown in *Table 2.3.*

2.3.2.1 Respiratory hospital admissions (RHA)

The results for the European domain targeted (*Table 2.3*) indicate 16,400 cases of RHA per year in the 1996–2015 period, which will increase by 3,800 cases in the RCP8.5 2071–2100 scenario. The external costs associated with this pathology represent EUR 87.1 million in the present climate, increasing in the future scenario by EUR 20.5 million (that is, an increase in cases and costs of +23 %).

Table 2.3: *Mean number of cases (in miles of cases) as associated costs (in millions of euros) 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 ($x10^3$) (1996-2015)	ΔCases ($x10^3$) (2071-2100)	Costs (M€) (1996-2015)	ΔCosts (M€) (2071-2100)
Respiratory Hosp. Adm. (RHA)	16.4	+3.8	87.1	+20.5
Cerebrovascular Hosp. Adm.(CHA)	31.9	+7.9	214.8	+53.1
Congestive Heart Failure (CHF)	117.1	+28.9	1288.3	+318.3
Chronic Bronchitis (CB)	310.6	+76.8	11982	+2962.8
Lung Cancer (LC)	47.7	+11.8	764.7	+189.1
Premature Deaths (PD)	418.7	+94.9	158970	+27346.0

If local differences in RHA are established (*Figure 2.2*), the highest number of present cases is found in the north of the study area, in countries such as Belgium and the Netherlands and in the western regions 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 fewer than 0.25 cases per year and 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 and northern Europe a slight decrease in RHA cases is projected (up to -4 cases per year cell) in localized cities located in Germany (Berlin) and 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 such as Paris, Cologne and Bucharest the present cost of RHA may reach up to EUR 1 million. For the future scenario, external costs are expected to increase in various European areas, especially in eastern Europe, an area which barely had costs associated with it in the present climatology, and in southern countries like Spain and Italy. In these last-mentioned areas, the costs increase by more than EUR 0.5 million per year and cell for 2071–2100 with respect to the 1996–2015 period.

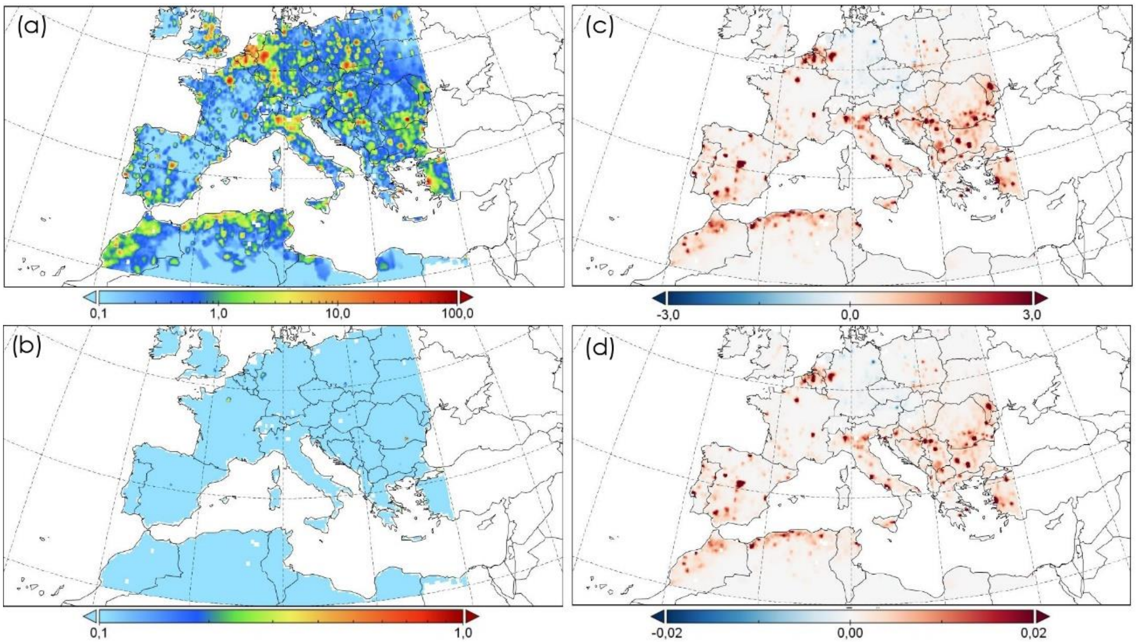

Figure 2.2: *(a) Present cases of respiratory hospital admissions (RHA) and (b) associated costs, in millions of euros. (c) Changes projected in RHA cases and (d) changes in costs (millions of euros) under the RCP8.5 scenario (2071–2100).*

RHA depends both on PM levels and SO_2 (also included in the PD estimation). The areas with a larger impact on future RHA are those where power plants and other facilities of energy production are located. In that case, the impacts on eastern countries are higher due to the high sulfur-content fuels on which their economies are based (Colette et al., 2012; Pozzer et al., 2012; Geels et al., 2015). Henceforth, most hospital admissions occur in European megacities and eastern Europe, with poor air quality levels causing respiratory damage.

2.3.2.2 Cerebrovascular Hospital Admission (CHA)

Table 2.3 indicates a total number of 31,900 cases of RHA per year in the 1996–2015 period (external cost of EUR 214.8 million), with an associated increase for the whole domain of 7,900 cases in the RCP8.5 2071–2100 scenario (increase in costs: EUR 53.1 million); that is, overall cases and costs will increase by +25% at the end of the 21st century with respect to the present situation.

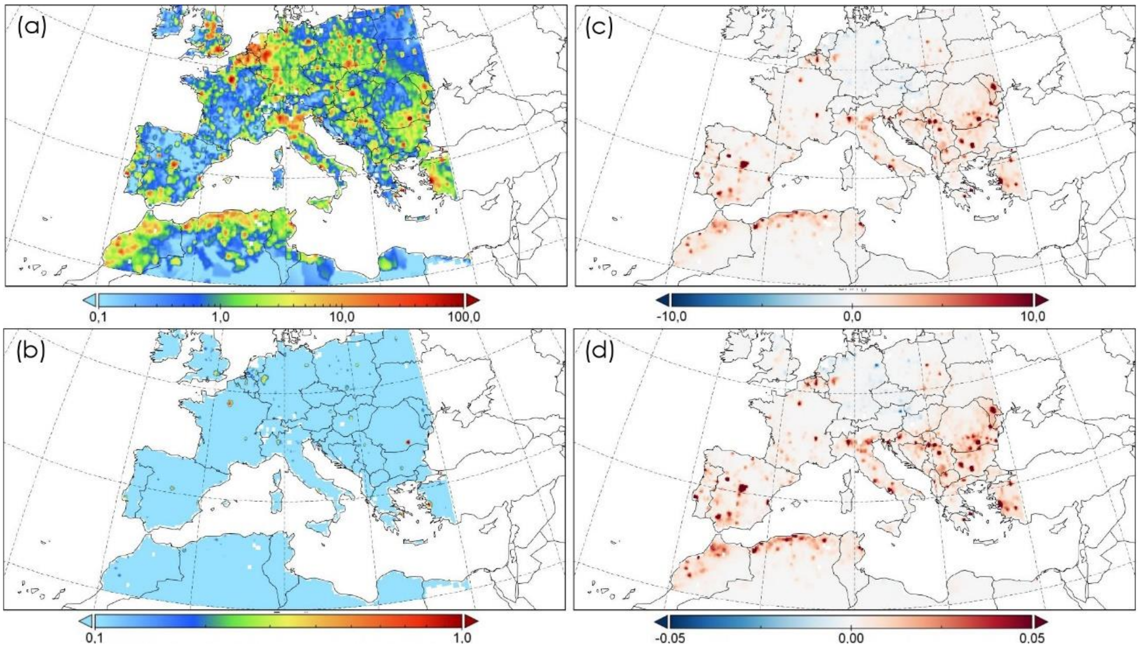

Figure 2.3: *(a) Present cases of cerebrovascular hospital admissions (CHA) and (b) associated costs, in millions of euros. (c) Changes projected in CHA cases and (d) changes in costs (millions of euros) under the RCP8.5 scenario (2071–2100).*

Regarding spatially distributed CHA, up to 400 cases per year are found in the city of Bucharest (*Figure 2.3*), with an associated external cost of EUR 2.5 million. Many of the European megacities exceed the 100 cases for the present period.

The countries with highest admission numbers are Belgium, the Netherlands and Germany. The northern half of Iberian Peninsula is the area least affected by CHA pathology. With respect to the differences with the 2071–2100 RCP8.5 scenario, the spatial pattern follows the same structure as for RHA cases shown in *Figure 2.2*, 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 fewer cases per year and cell). The increase in costs in the future scenario can reach up to EUR +2 million in large cities such as Madrid, Bucharest and Paris, while the decrease in costs in areas with reduced CHA such as Berlin and Vienna does not exceed EUR -0.5 million.

2.3.2.3 Congestive Heart Failure (CHF)

As pointed out in *Table 2.3*, there are 117,100 cases of CHF per year over Europe in the 1996-2015 period, with an associated external cost of EUR 1.3 billion. Future climate change will increase the cases of CHF by +24% (28 900 cases for the entire domain), also increasing the associated costs by the same percentage (increase of EUR 318.3 million in external costs for the period 2071–2100).

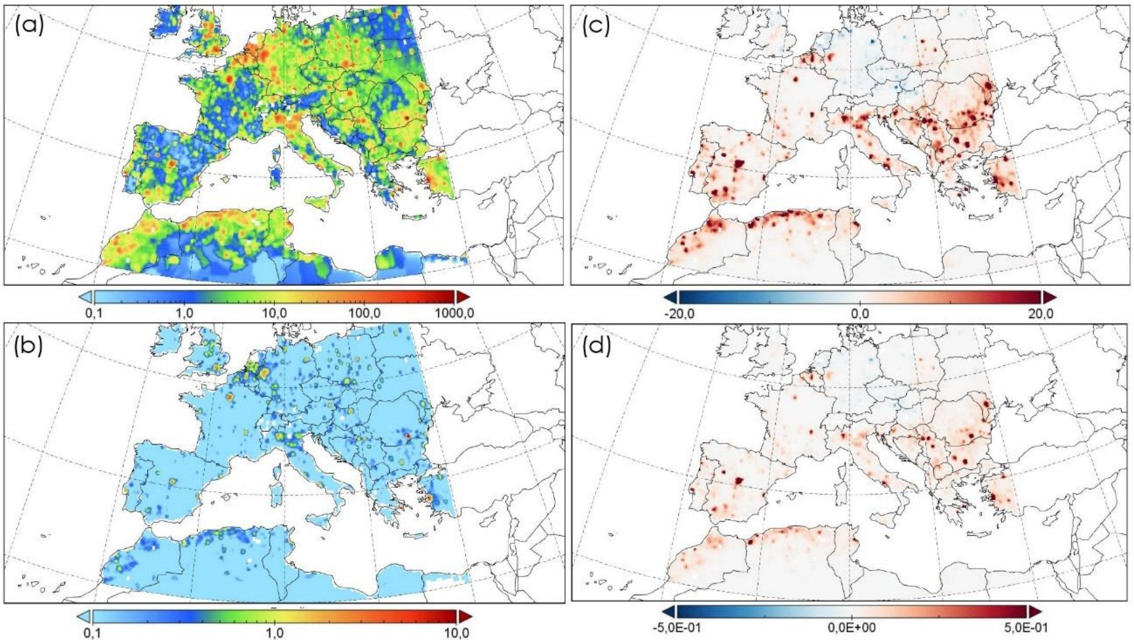

Figure 2.4: *(a) Present cases of congestive heart failure (CHF) and (b) associated costs, in millions of euros. (c) Changes projected in CHF cases and (d) changes in costs (millions of euros) under the RCP8.5 scenario (2071–2100).*

With respect to the spatial distribution of CHF (*Figure 2.4*) within the target area, once again most of the CHF cases are located in Belgium and the Ruhr area; however outlying hotspots appear in the largest European cities (London, Paris, Madrid), with over 1000 cases per year in all the cities (costs >EUR 10 million). The highest number was found over the city of Bucharest (over 1500 cases per year in all the city, with an associated cost of over EUR 16 million). 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 high vehicle traffic, which significantly contributes to CO and NO_x emissions.

CHF cases are widely distributed throughout the study area, with values generally fewer than 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, there is an increase of CHF close to 1000 cases in Bulgaria (Sofia and Craiova) and Moldova (Chișinău), with an associated increase in costs up to EUR 11 million. Once again, a decrease in cases (-36 cases per year cell) and associated costs (variations of EUR -0.4 million per year cell) is found in central Europe cities such as Vienna and Berlin for the 2071–2100 RCP8.5 scenario.

2.3.2.4 Chronic Bronchitis (CB)

Table 2.3 indicates that CB cases exceed 310,600 cases per year in the whole target domain for the 1996–2015 period (cost EUR 12 billion), which will increase by 76,800 cases in the RCP8.5 scenario (2071–2100), also increasing the cost by EUR 3.0 billion in the whole of Europe covered by the simulation domain (+25 %).

The CB cases are unevenly distributed over Europe (*Figure 2.5*). This pathology is distributed throughout the study area analogously to CHA (*Figure 2.3*), since the exposure–response coefficient for CB and CHA only depends on the concentration of particulate matter. Cases exceed 1,000 per year (over EUR 50 million) in cities such as Madrid, Paris, Brussels and Bucharest, with a maximum in the last mentioned city of 3,892 cases for the present period study (costs of EUR 150 million per year). Areas such as northern Italy and 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 Chișinău (Moldova), Bucharest (Romania) and Sofia (Bulgaria), where future increases in CB cases may exceed 2,600 (increase in external costs of over EUR 100 million). Meanwhile in some cities of Germany, Austria and the Czech Republic these pathology cases could decrease by up to almost 100 (EUR -4 million per year cell decrease in costs).

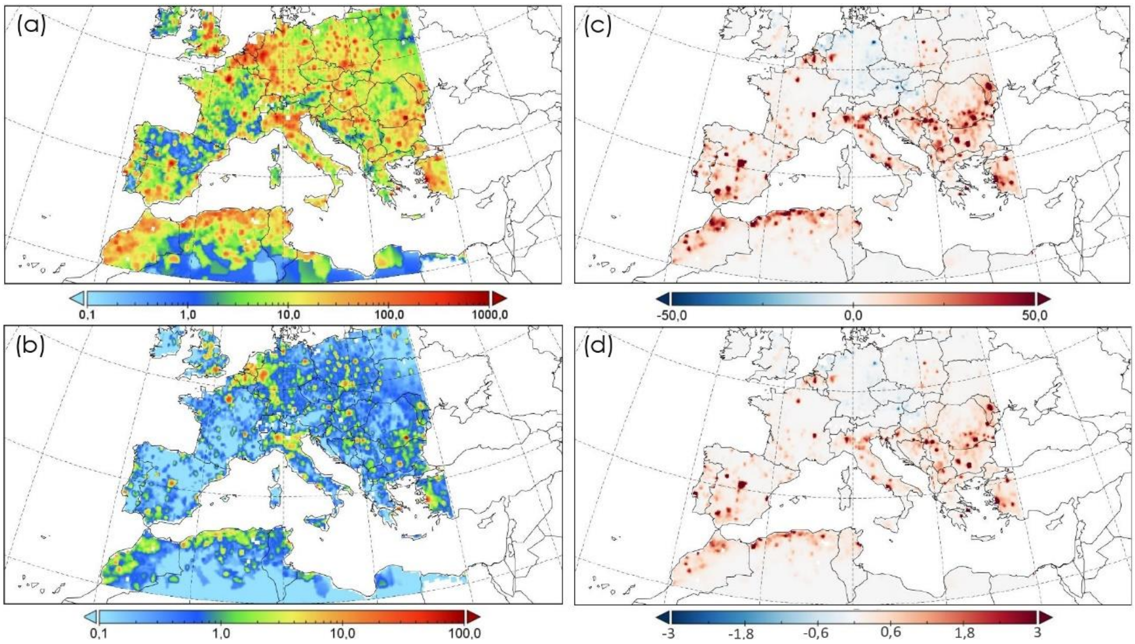

Figure 2.5: *(a) Present cases of chronic bronchitis (CB) and (b) associated costs, in millions of euros. (c) Changes projected in CB cases and (d) changes in costs (millions of euros) under the RCP8.5 scenario (2071–2100).*

2.3.2.5 Lung Cancer (LC)

Regarding LC, *Table 2.3* estimates 47,700 cases per year in Europe for the present climatology, with an associated cost of EUR 765 million. The projected increase by 2071–2100 reaches +11800 extra cases in the RCP8.5 scenario, with an increase in costs of EUR +189 million (+25% of cases and cost increase).

The results for the spatial distribution of LC (*Figure 2.6*) indicate that LC principally affects central and northern Europe, with widespread hotspots throughout the region. The maxima are found over European megacities (600 cases per year cell in the present climatology; costs over EUR 10 million). Countries with the widest affected areas are Belgium and the Netherlands, with a significant number of cases in Germany, northern Italy and southern Poland as well. An increase of over 400 LC cases per year and cell (associated increase in cost of EUR 6.5 million per year cell) is expected for the 2071–2100 period over southern Europe (Madrid, Rome, Bucharest, Sofia and Belgrade), with decreases of around 10 cases per 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).

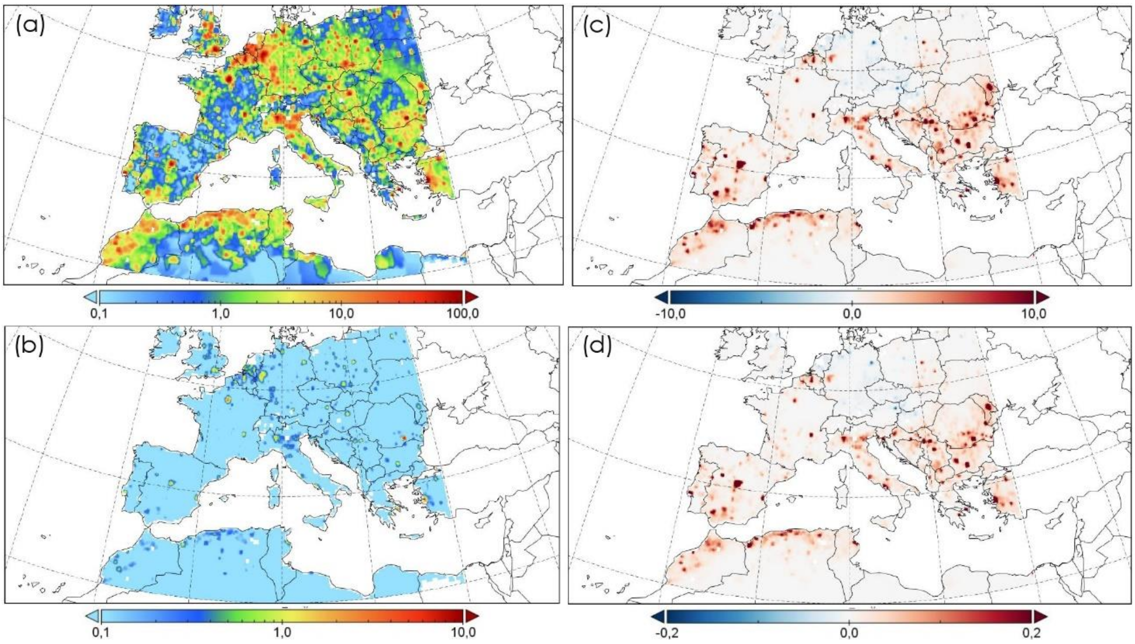

Figure 2.6: *(a) Present cases of lung cancer (LC) and (b) associated costs, in millions of euros. (c) Changes projected in RHA cases and (d) changes in costs (millions of euros) under the RCP8.5 scenario (2071–2100).*

2.3.2.6 Premature Deaths (PD)

Finally, the variable PD covers chronic mortality and acute mortality as defined in 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 years). Acute mortality depends on SO_2 levels and SOMO35, which is estimated as the sum of means over 35 ppb for the daily maximum 8 h values of ozone.

Estimates of 418,700 cases per year in the target domain are provided in *Table 2.3* for 1996–2015, with a huge associated cost (EUR 159 billion). The projected increase in the RCP8.5 for the years 2071–2100 reaches +94,900 extra cases, that is, an increase in costs of over EUR 27 billion (+17% of cases and cost increase).

The dominant pathology over the entire domain (*Figure 2.7*) is PD, especially over central Europe, Belgium, the Netherlands, Germany, Poland, Italy and Bulgaria. These countries have a high number of cases for the whole country. Hotspots are again located over large cities, exceeding 1,000 cases per year cell and even reaching 4,314 cases in several cities like Paris and London (associated external cost over EUR 700 million 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 European cities such as Madrid (Spain) and eastern European cities such as Belgrade (Serbia), Bucharest (Romania) and Sofia (Bulgaria) PD may increase up to 2,400 cases per year (EUR +450 million in several megacities), in cities of countries such as Germany (Berlin, Hamburg), France (Paris) and the United Kingdom (London, Manchester, Newcastle) a decrease of more than 200 cases per year and cell is projected (reduction of costs over EUR 31.5 million per year cell).

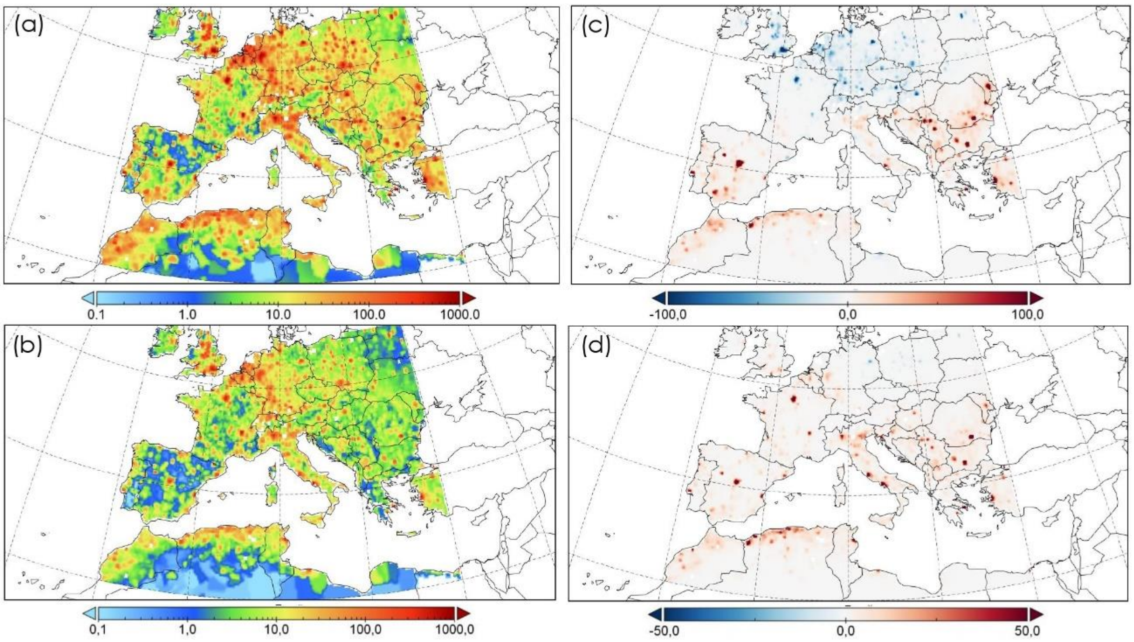

Figure 2.7: *(a) Present cases of premature deaths (PD) and (b) associated costs, in millions of euros. (c) Changes projected in PD and (d) changes in costs (millions of euros) under the RCP8.5 scenario (2071–2100).*

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 deaths (Tagaris et al., 2010; Geels et al., 2015). In contrast, more northern cities such as Berlin and Vienna will benefit from a better air quality in the future projections and a decrease in the number of cases and, in consequence, in 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.

2.4 Conclusions

As proposed in the objectives of this contribution, a relationship was established between air pollutant levels and the impacts on several human pathologies. There are two reasons for us carrying out this study: (1) exceedances of the limit values regulated by the European directives or the World Health Organization for several pollutants over some European areas and (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 conclusions obtained in this work).

The statistical epidemiological study (corroborated later by the modelling results in this same contribution) identifies a clear relationship between pathologies and air pollution by PM, especially in central European countries. The highest coefficients of correlation in the epidemiological study are found for total deaths and particulate matter (TD–PM10) in Germany, Slovenia and the Czech Republic and for deaths caused by respiratory diseases (relationship DRD–PM10) in Hungary and Italy. 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 significantly impact societal costs due to the damage to population health caused and are heterogeneously distributed over Europe, as are the impacts expected due to climate change. Several countries, such as Moldova and 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.

Premature deaths are the most important pathology in the study area in terms of costs (EUR 158 billion per year, that will increase by 17% in the future RCP8.5 2071–2100 projection) and cases (418,700 cases per year increased by 94,900 per 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 south-eastern Europe) because of the changes projected in PM and O_3 (the latter is related to PD, which is expected to increase 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 through reduced levels of air pollution (mainly PM2.5), as also pointed out by Tagaris et al. (2010).

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

Chapter 3

Contribution of fine particulate matter to present and future premature mortality over Europe: a non-linear response

The World Health Organization estimates that around 7 million people die every year from exposure to fine particles (PM2.5) in polluted air. In this contribution, the number of premature deaths in Europe from different diseases associated to the ambient exposure to PM2.5 have here been studied both for present (1991-2010) and future periods (2031-2050, RCP8.5 scenario). Non-linear exposure-response functions were used to estimate the premature mortality due to PM2.5, following the methodology developed by Burnett et al. (2018) and Lelieveld et al. (2019). Future population dynamics have been obtained from the 2050 United Nations (UN) Population Projections. The WRF-Chem online-coupled climate/chemistry model has been used for providing air quality data, operated over a Euro-CORDEX compliant simulation domain. The mortality endpoints included in this study are Lung Cancer (LC), Chronic Obstructive Pulmonary Disease (COPD), Cerebrovascular Disease (CEV), Ischemic Heart Disease (IHD), Lower Respiratory Infection (LRI) and other Non-Communicable Diseases (other NCDs). Different risk ratio and baseline mortalities for each disease end each age range have been estimated individually. The results indicate that 895,000 present premature deaths per year in Europe are associated to fine particles, with a 72% increase in 2050s (1,540,000 per year for the future period); meanwhile population decreases from 808 to 806 million according to the UN estimations. The results show that IHD is the main cause of mortality in Europe (around 47%) in both the present and future period. Despite marked regional differences, overall, all the endpoints included in this study will increase in the future period due to a changing climate but especially due to changes in population dynamics (aging of population).

3.1 Introduction

As stated by the World Health Organization (WHO), 9 out of 10 people breathe polluted air (WHO, 2018a; Chen, 2019; Kadaverugu et al., 2019). This means that most of the world population is threatened by this “invisible killer” (O’Connor, 2019). Nowadays, the evidence of the impacts of air pollution on human health is clear and has been widely studied in the last few decades (e.g. Pozzer et al., 2012; Silva et al., 2013; Cohen et al., 2017). The effects of air pollution on human health are plentiful, leading to an increase of the morbidity, a general decrease in the life expectancy, or even premature or acute death (Brook et al., 2010; Héroux et al., 2015). Moreover, air pollution strongly impacts premature deaths attributable to non-communicable diseases (NCDs) (Nghavi et al., 2017). NCDs (also called chronic diseases) are long-duration diseases, resulting from a combination of some factors (genetic, physiological, environmental and behaviours) and kill 41 million people each year (71% of global deaths) (WHO, 2018b). 48% of deaths caused by NCDs are considered premature because they occurred before the age of 70 (Magnusson, 2019).

Different air pollutants have diverse effects on health, but the pollutant with the most important effect is fine particulate matter (particulate matter with a diameter under 2.5 μm, PM2.5) (Burnett et al., 2018; Liang et al., 2018). The WHO estimates that around 7 million people die every year from exposure to fine particles in polluted air that lead to diseases such as stroke, heart disease, lung cancer, chronic obstructive pulmonary diseases and respiratory infections, including pneumonia (WHO, 2018a). A number of studies have revealed the influence of anthropogenic emissions and atmospheric composition on the effects of ambient particulate matter (e.g. Liu et al., 2009; West et al., 2009; Anenberg et al., 2014; Lin et al., 2012; Ravishankara et al., 2012; Lin et al., 2017; Im et al., 2018; Liang et al., 2018; Palacios-Peña et al., 2019).

The exposure to outdoor particulate concentration is a more important health risk factor than previously thought (Burnett et al., 2018). Fine particles can damage different organs such as lungs, heart or brain; and can lead to premature death. Nowadays, mechanisms of action are not entirely clear, but there are enough evidences about the relationship between PM2.5 and its impacts on human health (e.g. Liu et al., 2009; Pope et al., 2009; Brook et al., 2010; Pope et al., 2011; Anenberg et al., 2014; Ford and Heald, 2016; Hvidtfeldt et al., 2019; Lelieveld et al., 2020; among many others). Münzel et al. (2018) point out some of the impacts caused by fine particulate matter such as inflammation, oxidative stress and vascular dysfunction. The concentration levels and the exposure time to PM2.5 are other factors to take into account. Fine particles can produce damage even in small concentrations (e.g. Beelen et al., 2014). Regarding the exposure time, not only short-term exposure has been associated with increases in daily mortality due to respiratory and cardiovascular causes mainly; but long-term exposure also leads to chronic effects on human health (e.g. Hoek et al., 2002; Krewski et al., 2009; Brook et al., 2010; Pope et al., 2011; Bell et al., 2014; Burnett et al., 2014; Guan et al., 2019).

Epidemiological studies brought to light that both short and long-term exposures to particulate matter are associated with elevated rates of premature mortality (Anenberg et al., 2014; Liang et al., 2018). Recent assessments evinced the large number of global deaths due to this pollutant. For instance, Silva et al. (2013) estimated 2.1 million premature deaths worldwide. This number was increased in different contributions to 2.8 million (Liang et al., 2018), 3.2 million (Lelieveld et al., 2015) or 4.2 million (Cohen et al., 2017). In addition, these health damages and mortality cause important economic losses (e.g. Brandt et al., 2013a, 2013b; Im et al. 2018). Recently, Tarín-Carrasco et al. (2019) estimated that premature deaths related to air pollution are the most important environmental problem in Europe related to costs (158 billion euro per year) increasing by 17% in the future RCP8.5 2071-2100 scenario only due to climate penalty.

When considering these environmental and health problems for future climate change scenarios, the complexity of the problem increases, since the estimation of climate penalty on PM2.5 concentration is still intricate because of the uncertainties related to projections of temperature and precipitation, as well as wildfires and natural emissions under future climate change scenarios (Jacob and Winner, 2009; Fuzzi et al., 2015; Fiore et al., 2015). Despite these uncertainties, an important number of works agree that climate change modifies the chemistry, transport and deposition of some pollutants, worsening regional air quality (e.g. Jacob and Winner, 2009; Jiménez-Guerrero et al., 2013a, 2013b; Liu et al., 2016) and in consequence, increasing premature deaths over Europe (e.g. Geels et al., 2015; Doherty et al., 2017; Im et al., 2018; Tarín-Carrasco et al., 2019) and in the whole world (e.g. Lelieveld et al., 2015; Silva et al., 2017; Kinney, 2018).

Hence, the objective of this study is to estimate the premature mortality associated to fine particulate matter over Europe due to different endpoints or causes of premature mortality. To cope with this objective:

(1) the sensitivity of the mortality estimation with two different non-linear methodologies (GEMM and GBD) is compared; (2) the number of mortality cases due to PM2.5 of 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 NDCs) during the present (1991-2010) are estimated; and (3) the difference on the future (period 2031-2050) mortality due to climate change action (under the RCP8.5 scenario) and population dynamic is calculated considering changes in PM2.5 concentration and population.

3.2 Methodology

The number of premature deaths in Europe has been estimated by using exposure-response functions. Different methodologies, scenarios, periods and/or emissions are used in the scientific literature to estimate the impacts of outdoor pollution on human health. In the present work, two different non-linear functions have been applied for the calculation of premature mortality due to exposure to PM2.5: the Global Burden Disease (GBD) and the Global Exposure Mortality Model (GEMM) methodologies. With respect to GBD, Burnett et al. (2014); Lelieveld et al. (2015); Cohen et al. (2017) or Liang et al. (2018), among others, used this methodology to calculate different cause-specific mortality all over the entire world or over regional areas such as Europe. The GEMM methodology was developed by Burnett et al. (2018) and was also used in Lelieveld et al. (2019). A brief description of the methodologies used is presented below, together with other methodological aspects.

3.2.1 Estimation of risk ratios and mortality due to exposure to PM2.5

As previously commented, premature mortality is estimated using exposure-response functions, which describe the association between PM2.5 and non-accidental mortality. *Equation 3.1* describes the exposure-response function followed in this work. This equation is based on epidemiological relationships between air pollution concentration and mortality and it is applied in each grid cell where information about air pollution and population is available (Lelieveld et al., 2015, 2019):

$$\Delta M = y_0 \, \frac{RR - 1}{RR} \, Pop \tag{3.1}$$

where ΔM is premature mortality for each disease; RR is the risk ratio, which estimates the relative risk of exposure to a specific pollutant; y_0 is the baseline mortality rate; and Pop refers to the exposed population. y_0 varies for each mortality endpoint, age and European region and is estimated annually by the WHO for each gender. Population densities used in the present study account for both male and female dwellers for the year 2017 (the last year available in the Global Health Data Exchange) (GHDE, 2019). RRs and hence premature mortality have been estimated for each pathology (given below) and for different age groups: 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.

As aforementioned, two different non-linear methodologies for estimating the RRs were applied in this study. The GBD methodology determines the RR values for each pathology and age range by using the following expression (*Equation 3.2*):

$$RR = 1 + \alpha\,\{1 - \exp[-\gamma(z - z_0)\delta]\} \qquad (3.2)$$

A Monte Carlo method has been applied to determine α, γ and δ for each disease and age range (Burnet et al., 2018). z refers to the PM2.5 concentration in μg m^{-3} and z_0 is the concentration threshold for PM2.5, below which no risk is assumed for human health. α, γ, δ and z_0 were obtained from the Global Burden Disease study (GBD, 2016).

In the second methodology, coming from the Global Exposure Mortality Model (GEMM) (Burnett et al., 2018), RRs are calculated through a number of hazard ratio functions. These functions are based on 41 cohort studies from 16 countries and model the association between PM2.5 and non-accidental mortality. Hence, the methodology of Burnett et al. (2018) as implemented in Lelieveld et al. (2019) gives the following expression (*Equation 3.3*):

$$RR = \exp\left(\frac{\theta \log\left(\frac{z}{\alpha}+1\right)}{1+\exp\left(-\frac{z-\mu}{v}\right)}\right), \textit{ where } z=\max(0, PM2.5 - 2.4\ \mu g/m^3) \qquad (3.3)$$

where θ, α, μ and v are variables obtained from Burnett et al. (2018) and z is the PM2.5 concentration. Concentrations below a certain threshold (2.4 μg/m^3) are not taken into account because of the high uncertainty associated to the limited PM data available from cohort studies below this value.

With respect to the studied pathologies, Lung Cancer (LC), Chronic Obstructive Pulmonary Disease (COPD), Cerebrovascular Disease (CEV), Ischemic Heart Disease (IHD) and Lower Respiratory Infection (LRI) were studied using GBD methodology. The category of non-accidental diseases, which was defined as NCD+LRI; and the so-called 'other NCDs', defined as the subtraction of the above categories to NCD+LRI, were added when using GEMM. Both methodologies, GBD and GEMM, use the same baseline data, population and concentration of PM2.5 pollutants for the estimation of the premature deaths associated to each pathology.

In the present study, Europe was divided into three different regions following Couvidat et al. (2018) and Pandolfi et al. (2018) with different values of y_0

(baseline mortality rate) for each region. This division takes into account a number of different variables like the type of public health system, the economy of the country and the climatological characteristics. Hence, the final regions (*Figure 3.1*) are: (1) Western Europe (Portugal, Spain, France, Italy, United Kingdom and Ireland); (2) Central Europe (Denmark, Finland, Norway, Sweden, Austria, Belgium, Germany, Luxembourg, The Netherlands and Switzerland); and (3) Eastern Europe (Turkey, Belarus, Bulgaria, Czech Republic, Hungary, Poland, Republic of Moldova, Romania, Russian Federation, Slovakia, Ukraine, Estonia, Latvia, Lithuania, Albania, Bosnia and Herzegovina, Croatia, Greece, Montenegro, North Macedonia, Serbia and Slovenia).

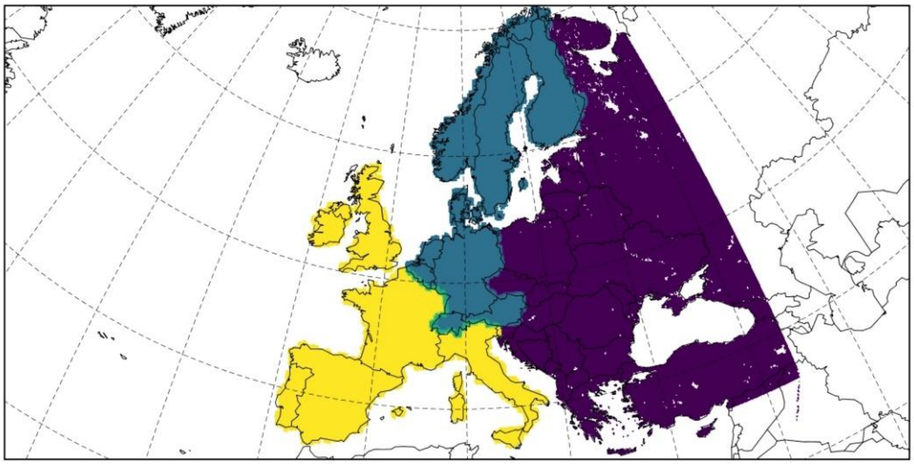

Figure 3.1: *Target domain and European regions included in this contribution: Western Europe (yellow), Central Europe (blue) and Eastern Europe (purple).*

3.2.2 Pollution data

Air pollution data for estimating present and future mortality under a climate change scenario come from chemistry-transport air quality simulations with constant anthropogenic emissions. The WRF-Chem online-coupled climate/chemistry model (Grell et al. 2005) version 3.9.1 with a horizontal resolution of 25 km has been used under the umbrella of the REPAIR and ACEX projects (Palacios-Peña et al., 2020) over the Euro-CORDEX (Jacob et al., 2020) compliant domain. The physical-chemical configuration has been summarized in *Table 3.1*.

The present reference period spans 1991-2010; and the future enhanced forcing scenario is represented by the period 2031-2050 under the RCP8.5 scenario developed by the Intergovernmental Panel on Climate Change (IPCC), which is at the top of radiative forcing scenarios among all the Representative Concentration Pathways (RCPs; Moss et al., 2010). The differences between these two runs will provide the changes in future air quality.

Table 3.1: *Physico-chemical parameterizations implemented in WRF-Chem simulations over Europe*

Parameterization	***Option***	***Reference***
Physics		
Microphysics	Lin	Lin et al. (1983)
Land Surface	NOAH	Tewari et al. (2004)
Longwave and shortwave radiation	RRTM	Iacono et al. (2008)
Cumulus	Grell 3D Ensemble	Grell and Dévényi (2002)
Planetary Boundary Layer	YSU	Hong et al. (2006)
Chemistry		
Aerosol	GOCART	Ginoux et al. (2001); Chin et al. (2002)
Gas-phase	RACM-KPP	Stockwell et al. (2001); Geiger et al. (2003)
Photolysis	Fast-J	Fast et al. (2006)
Anthropogenic and Natural emissions		
Anthropogenic emissions (constant)	ACCMIP	Lamarque et al. (2010)
Biogenic emissions	Model of Emissions of Gases and Aerosols from Nature model (MEGAN)	Guenther et al. (2006)
Dust emissions	GOCART	Goudie et al. (2001; 2006) (further details in Palacios-Peña et al., 2019)
Sea Salt emissions	GOCART	Chin et al. (2002)

Simulations were driven by the GCM CMIP5-experiment (Taylor et al., 2012). The r1i1p1 MPI-ESM-LR historical run (Giorgetta et al., 2012a) for the present period and the RCP8.5-forced r1i1p1 MPI-ESM-LR run (Giorgetta et al., 2012b) for the future. The evolution of CO_2, CH_4, and N_2O greenhouse gases in the regional model has been considered after Jerez et al. (2018). Vertical resolution is 29 vertical sigma levels with the top at 50hPa. The simulated periods were split into 5-year periods that were then continuously run with a spin-up period of 4 months following the recommendations of Jerez et al. (2020).

Due to the lack of dust concentrations from the boundary conditions, an outer domain with a spatial resolution of 1.32º covering the main source of Saharan dust emissions (Goudie et al., 2001; 2006) were used as in Palacios-Peña et al. (2019). This outer domain was run with spectral nudging in order to maintain a more realistic synoptic situation.

3.2.3 Population data in the European domain

Population data for Europe has been taken from the gridded dataset of NASA SocioEconomic Data and Applications Center (SEDAC) (http://sedac.ciesin.columbia.edu) Basic Demographic Characteristics, v4.11 (SEDAC, 2019). 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 km^2.

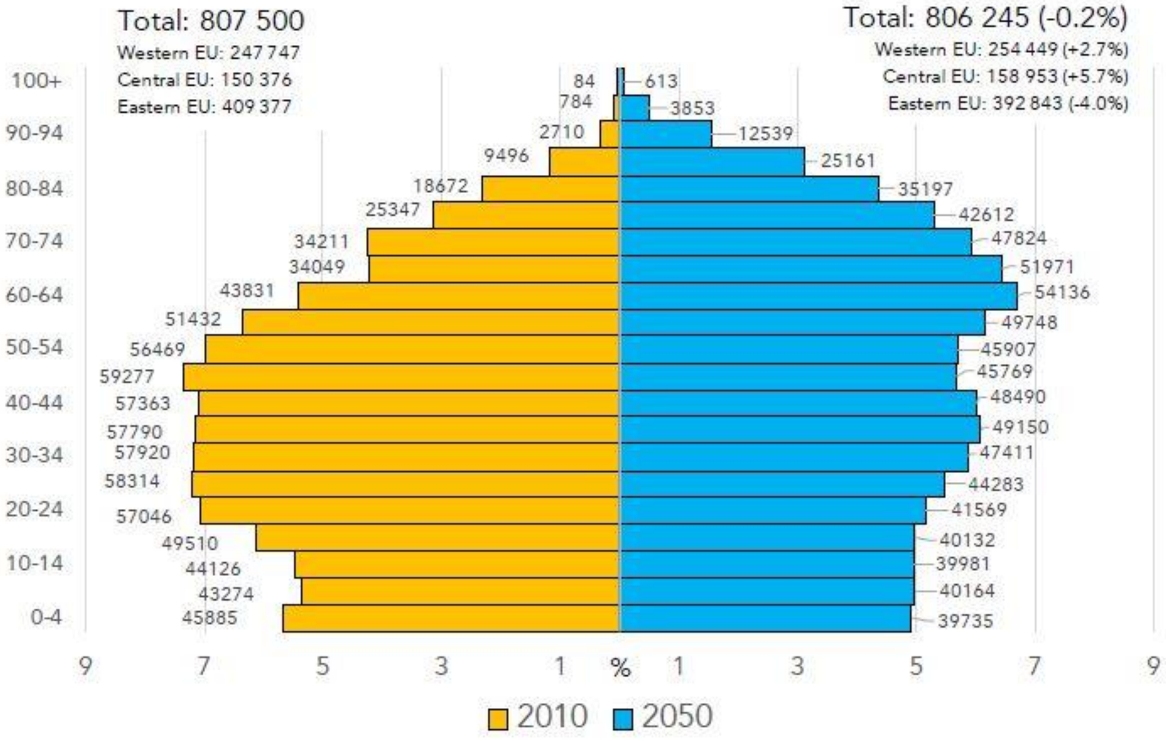

__Figure 3.2:__ Population pyramid by age range for the year 2010 (red, left) and 2050 (green, right). Population data for each range are in thousands. x-axis represents the percentual contribution of each age range to the total population.

Population data were interpolated to the Euro-CORDEX working grid to make it consistent with the gridded air pollution data. 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 Dynamics (UN, 2019). This includes both a development of the total national numbers but also the age distribution.

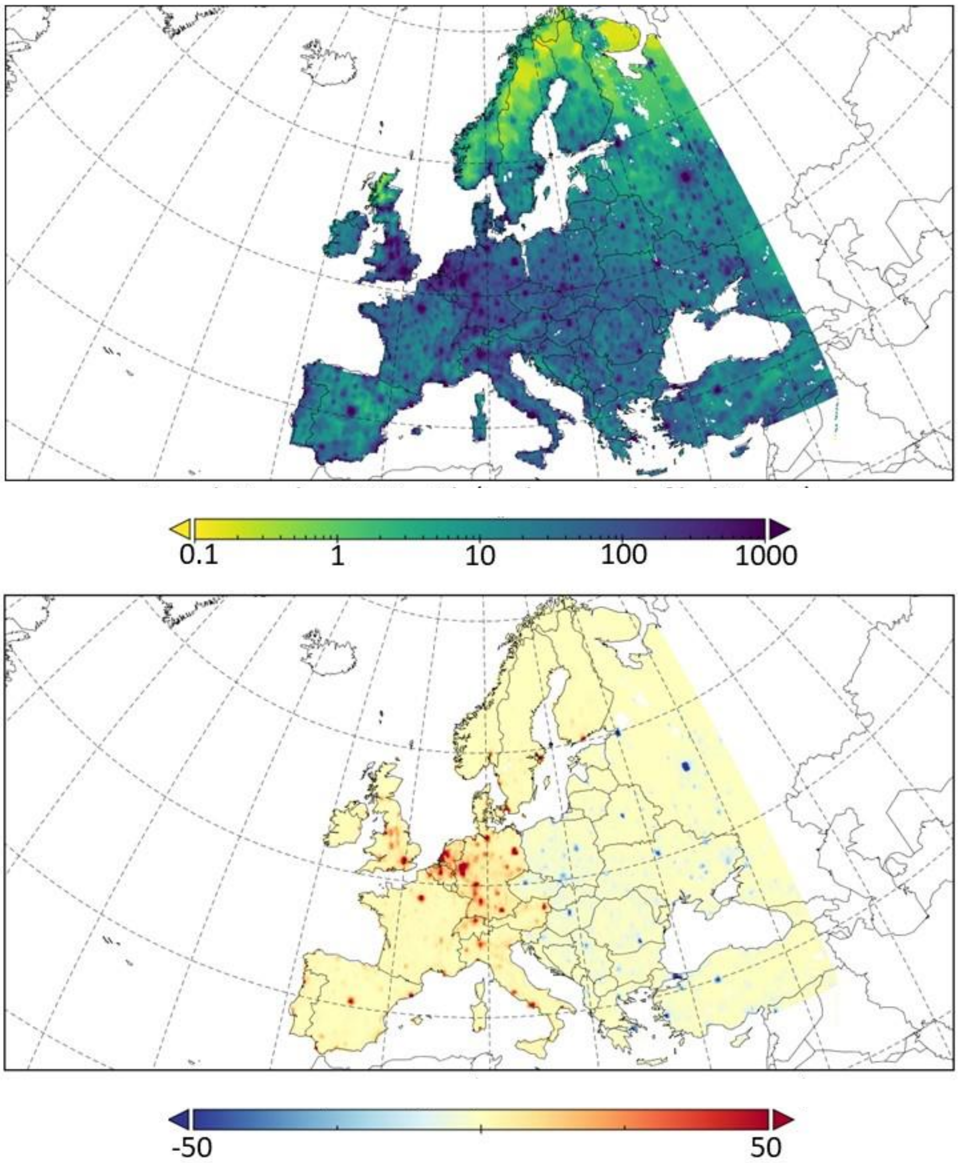

Figure 3.3: *Population density (pop/km^2) in each grid cell for the present case (top) and difference with UN-projected population in 2050 (bottom) over the European target domain (pop/km^2).*

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. The population pyramid both for the year 2010 and 2050 is presented in *Figure 3.2*. This Figure indicates a slight projected decrease of European population (808 vs. 806 million dwellers both for present and future population, respectively), especially over Eastern Europe (*Figure 3.3*). In addition, the projected data includes a higher population density over many urban areas, and a clear ageing 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 over 9% in the projected UN 2050 estimations.

3.3 Results and discussion

This section presents and discusses the results obtained. First, the RRs as estimated with both the GBD and GEMM methodologies are compared in order to establish the divergences appearing when using *Equations 3.2 and 3.3*. Afterwards, the GEMM methodology is used to estimate the premature mortality during the present and future periods and the differences between these periods are discussed. For the future period, the effects of climate change and the population dynamics were considered.

3.3.1 Premature deaths in GBD vs. GEMM methodologies

The following section shows the comparison between the two methodologies described above, GBD and GEMM. The annual mean surface PM2.5 concentration described above, averaged annually over 20 years (1991-2010) is shown in *Figure 3.4 (top).*

According to the Directive 2008/50/EC on ambient air quality and cleaner air for Europe, the PM2.5 limit value for the protection of human health is set to an annual mean concentration of 25 µg/m^3. Eastern Europe is the area where the highest PM2.5 concentrations are seen in the simulation for the current period. In most areas, the level is below the limit value, however, in some hotspots like Paris

(France), Krakow (Poland), Moscow (Russia) and the eastern part of Ukraine the concentration exceeds the limit value. *Figure 3.4 (bottom)* also shows the projected changes of air pollution associated to PM2.5 over Europe in the 2031-2050 under the RCP8.5 scenario, where the whose strong south-north dipole pattern (increase in southern Europe decrease for PM2.5 over northern Europe) has been widely discussed elsewhere (e.g. Jiménez-Guerrero et al., 2013a, 2013b; Tarín-Carrasco et al., 2019). In particular, PM2.5 over the Iberian Peninsula is projected to increase by >2 µg/m^3 as annual mean due to the changed climate.

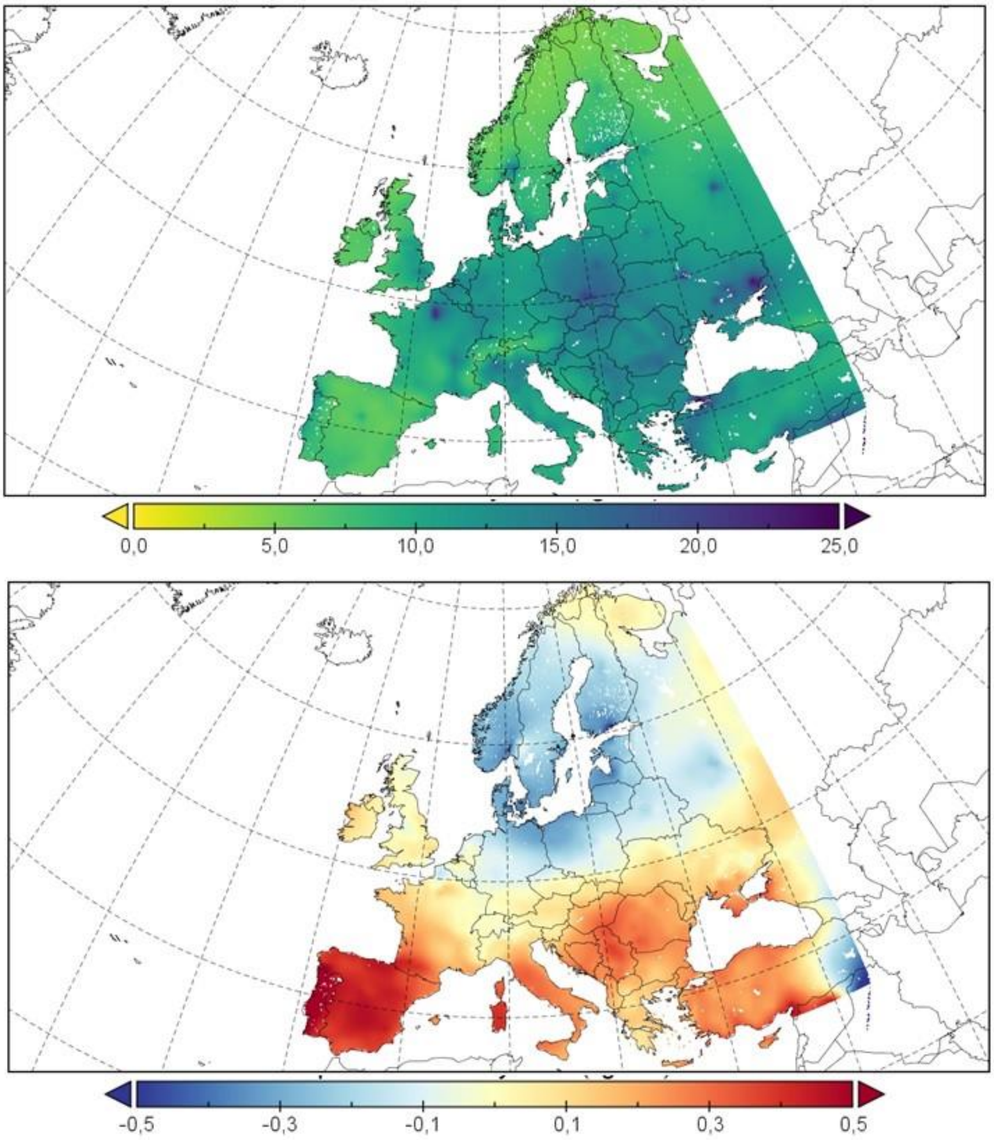

Figure 3.4: *(Top) Annual mean PM2.5 concentration over Europe during the present climatic period (1991-2010) and (bottom) the difference in the PM2.5 levels between the present and future period (2031-2050, RCP8.5) (as mean for present minus mean for the future).*

On the contrary, over northern Europe a decrease of the PM2.5 concentration (around 0.3 µg m^{-3}) is simulated. The latteris fact can be attributed to an increase of the precipitation over this area on the future (Jacob et al., 2018), which will entail a better air quality by enhancing the removal of particles (Hou et al., 2018). Conversely, in southern Europe a reduction in precipitation is expected under the RCP8.5, hampering the wet scavenging and worsening making the air quality to get worse (Jiménez-Guerrero et al., 2013a).

These concentrations are used as input to *Equations 3.2 and 3.3* in order to estimate the RRs. The differences between both equations are caused by the different number of cohort studies included in each methodology. The number of cases in the present period (1991-2010) estimated with GBD and GEMM methodologies are shown in *Table 3.2* and *Figure 3.5*.

Table 3.2: *Number of cases for Europe and percentage of each cause for GBD and GEMM for present period (1991-2010). Pathologies have been selected so they are comparable between the two methodologies*

	GBD		**GEMM**	
	Cases (x10^3)	%	Cases (x10^3)	%
LRI	7	1.5	42	6.7
LC	18	3.8	48	7.6
COPD	10	2.0	28	4.4
IHD	344	72.1	424	67.5
STROKE	98	20.6	87	13.8
TOTAL	**477**	**100**	**629**	**100**

The most noticeable difference is that GEMM estimates 150,000 more premature deaths per year due to PM2.5 in Europe than GBD (629,000 vs. 477,000 premature deaths estimated with GEMM and GBD, respectively). The main differences are found over Eastern and Western European regions (agreeing with the most polluted regions by particles in the present), with minor differences found for Central Europe (*Figure 3.6*). The largest differences are seen for some hotpots coinciding with the largest European cities. The area of southern United Kingdom also stands as the area with the highest differences, with nearly 0.05 cases per km^2 for GEMM.

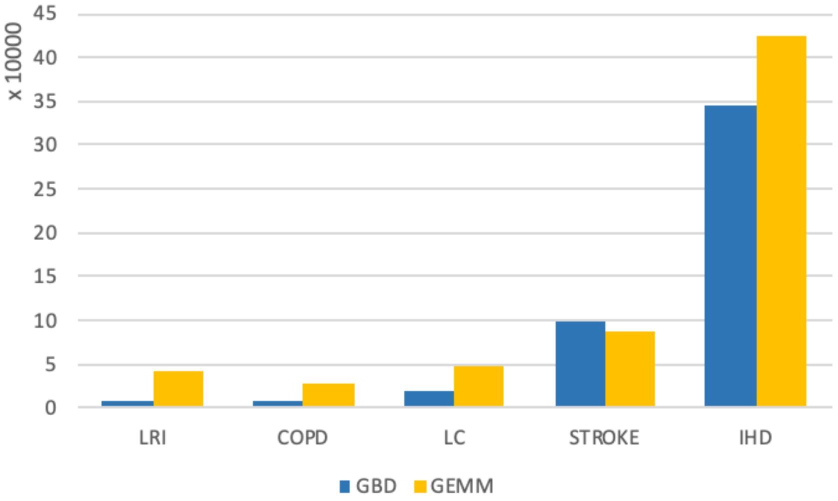

Figure 3.5: *Estimation of mortality cases per year (present period, 1991-2010) for GBD (blue) and GEMM (yellow) for premature deaths associated with LRI, COPD, LC, STROKE and IHD over Europe.*

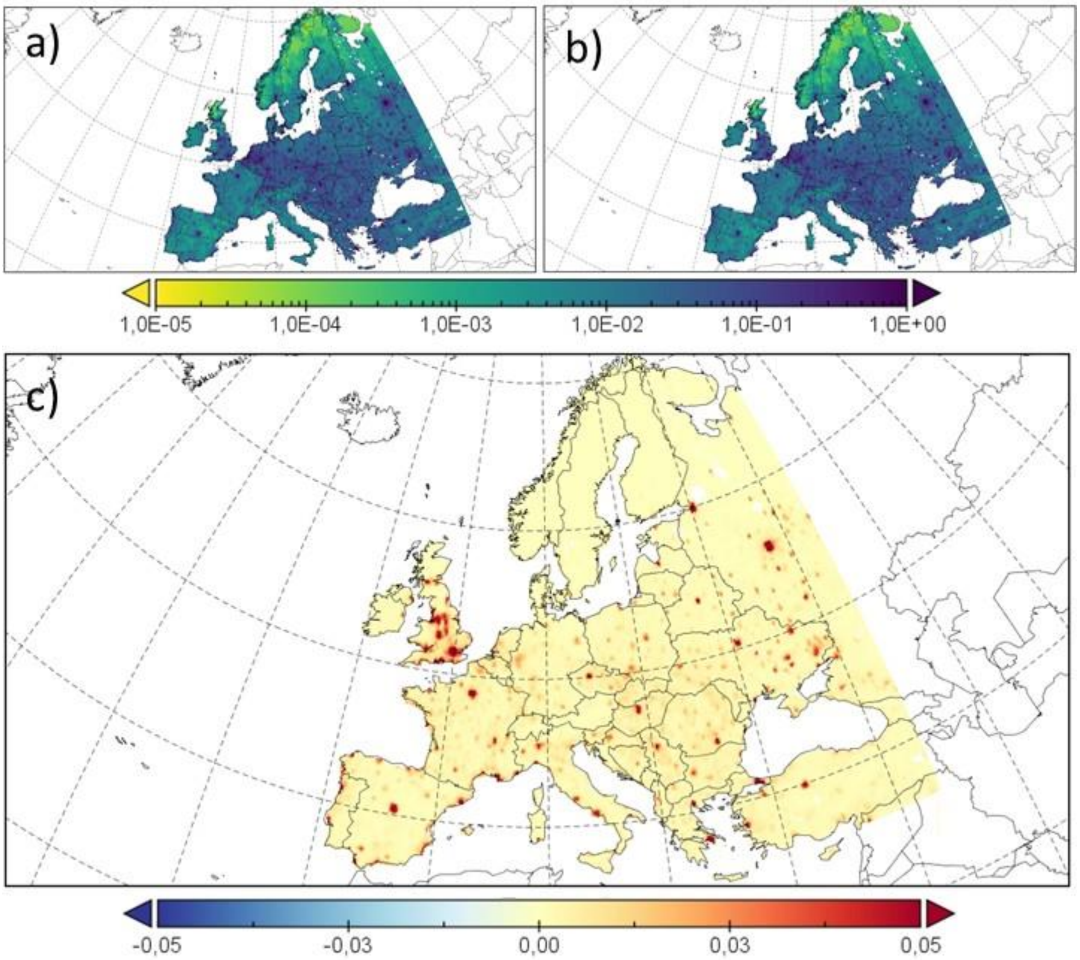

Figure 3.6: *Annual premature deaths estimated with the (a) GBD and (b) GEMM methods. (c) Difference in the number of premature deaths per year (all units: premature deaths per km^2) between GEMM and GBD methodologies.*

Although the percentages of deaths associated with each mortality are similar for GBD and GEMM (*Table 3.2*), the former methodology estimates more cases of premature deaths related to COPD than to LRI (10,000 vs. 7,000 premature deaths, respectively, in GBD) while GEMM shows an opposite behaviour (28,000 premature deaths for COPD vs. 42,000 for LRI). The GBD results presented in this contribution are slightly higher than those obtained by Lelieveld et al. (2015), who estimate a total of 375,000 deaths for a similar domain over Europe and during a similar period.

Total number of premature deaths is 477,000 in the present study, that is, ca. +20% higher than the aforementioned work. Comparing the results for each pathology, Lelieveld et al. (2015) estimate 1,000 deaths for LRI (7,000 in this contribution); LC 27,000 (18,000); COPD 13,000 (10,000); IHD 239,000 (344,000) and CEV 95,000 (98,000). That is, the main difference comes from the estimation of premature deaths associated to ischemic heart disease (+30% in this contribution).

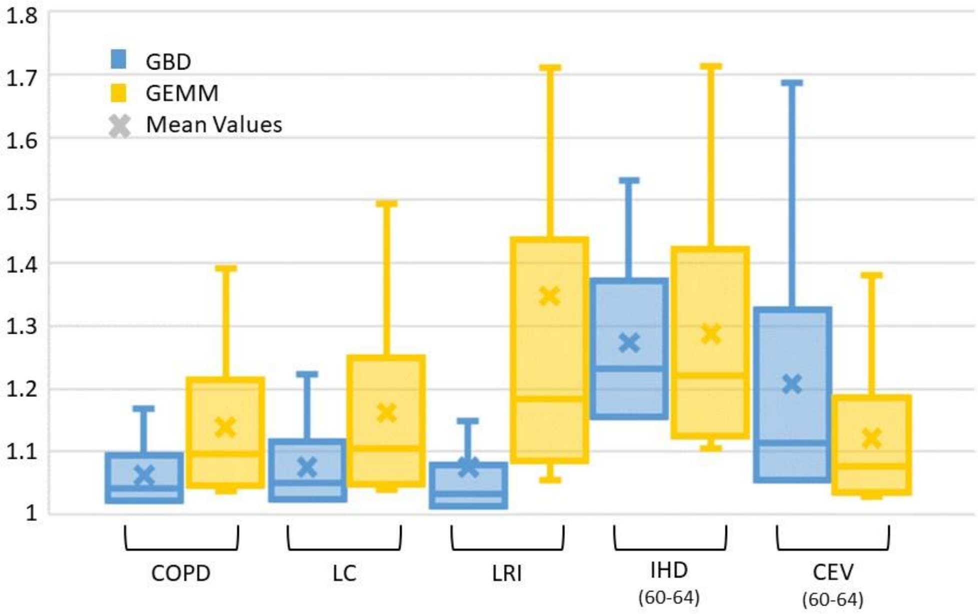

Figure 3.7: *Whisker plot of the Risk Ratios (RRs) for common GBD and GEMM diseases. The crosses represent the mean values of RRs over the European domain.*

Once the differences between GBD and GEMM have been stated, and the results have been put into context by comparing with previous literature, the causes for the differences between GBD and GEMM results have to be sought in the estimation of the different RRs (and their uncertainties) as calculated in *Equations 3.2 and 3.3*, since the same air pollution dataset has been applied. Hence, regarding RRs (*Figure 3.7*), it should be pointed out that the interquartile ranges, representative of the uncertainty of the estimation, are wider for GEMM.

In general, the RRs are higher for this latter methodology than for GBD, as shown both by the mean and the median values. The highest values of RR are obtained in GEMM for LRI and IHD with maximum mean values of 1.35 for LRI in GEMM. The difference for the LRI case between GBD and GEMM has to be highlighted, with a mean value of 1.09 for GBD and 1.35 for GEMM. COPD and LC also present a higher value of RR for GEMM (1.14 and 1.16 respectively), while RR for GBD are 1.06 and 1.08 for COPD and LC, in that order. Conversely, RR values for CEV in the GBD methodology are higher than those obtained by the GEMM methodology. Finally, no large differences can be noted between both methodologies for IHD, being the RR for GBD and GEMM 1.27 and 1.28, respectively. With respect to the uncertainties, GEMM generally presents a wider range in the estimation of RRs, except in the case of CEV.

According to the available literature, the RR are constant for the different age groups considered in this contribution for COPD, LC and LRI, while epidemiologic studies of risk factors indicate that IHD and CEV RRs declines with the logarithm of age (Glymour et al., 2008; Krewski et al., 2009; Pope et al., 2009; Singh et al. 2013; Burnett et al., 2014). The RRs for IHD and CEV also show a decrease, when age increases. Similar patterns were obtained by Burnett et al. (2014) and Cohen et al. (2017) for GBD and by Burnett et al. (2018) for GEMM.

Differences pointed out in the RRs are due to the different individual cohort studies reported in each methodology. The higher RR values obtained with GEMM methodology are caused by the higher number of cohorts exposed to a poor air quality taken into account in GEMM with respect to those included in GBD (Burnett et al., 2018). Henceforth, large differences are expected in the non-linear range of *Equations 3.2 and 3.3*. For these reasons (due to the higher number of cohort studies taken into account in GEMM and the areas where these cohorts come from, with annual levels closer to those presented here for large conurbations, that can add up to nearly 40 μg/m^3 of PM2.5 as annual mean), the following sections focus on applying the GEMM methodology.

3.3.2 Present (1991-2010) PM2.5-related premature mortality for Europe

Once the differences between both methodologies have been discussed, in this section the spatial distribution of annual mortality due to PM2.5 over Europe during the present period (1991-2010) is presented. This distribution was estimated by using the GEMM methodology (GBD is not shown, as discussed previously and for the sake of clarity, since the spatial patterns are analogous to those and GEMM). The different mortality endpoints studied in this work are shown in *Figure 3.8*. In order to be able to compare mortality associated with the different pathologies over the three different regions (Western, Central and Eastern Europe), *Table 3.3* summarizes the results found by region.

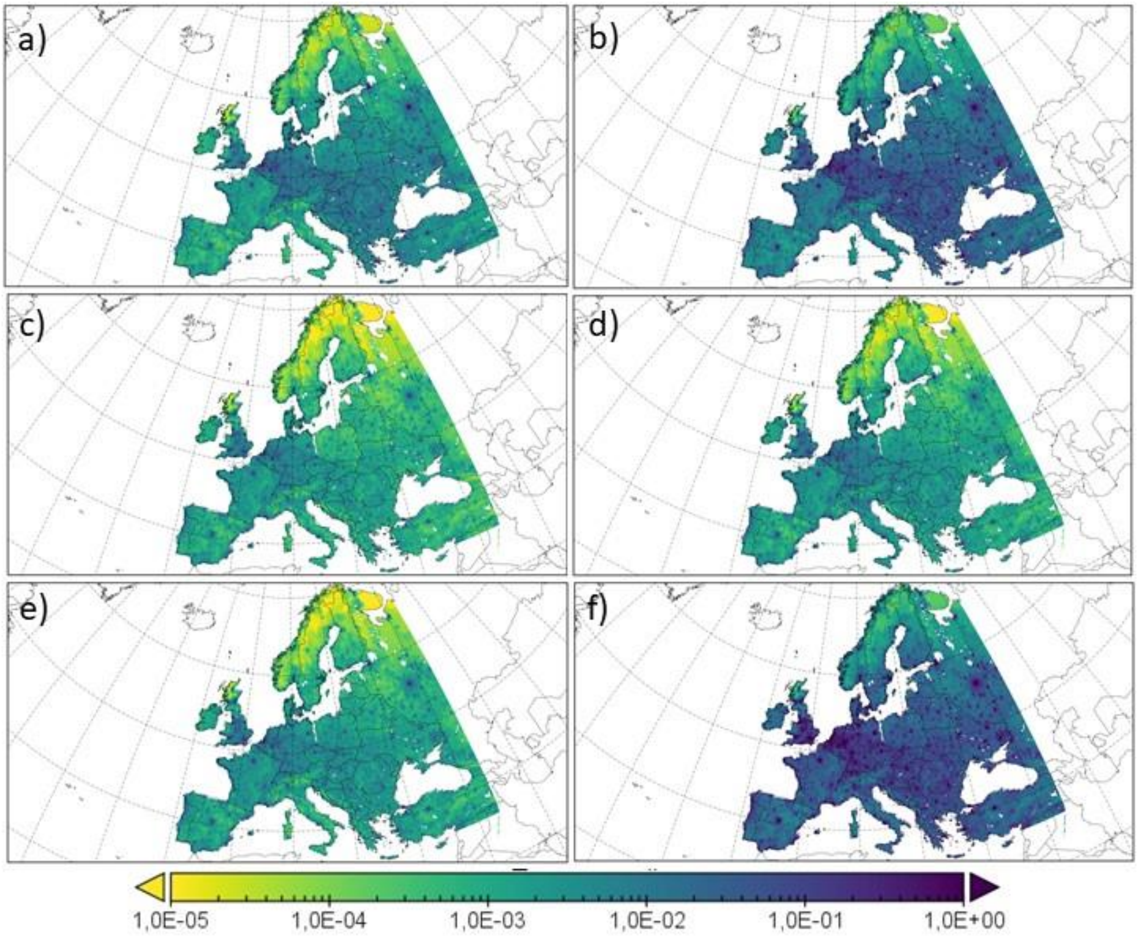

Figure 3.8: *Estimation of annual premature deaths associated with PM2.5 exposure in Europe per km^2. (a) CEV, (b) IHD, (c) COPD, (d) LC, (e) LRI and (f) All for the present period (1991-2010).*

Table 3.3: *Population and annual premature mortality estimation for the present period (1991-2010) for Europe, shown by geographic region (in thousands).*

	Pop. ($x10^6$)	CEV ($x10^3$)	IHD ($x10^3$)	COPD ($x10^3$)	LC ($x10^3$)	LRI ($x10^3$)	Other NCD ($x10^3$)	All ($x10^3$)
Western	248	8	43	9	14	12	89	175
Central	150	24	105	9	16	11	88	253
Eastern	409	55	277	10	17	19	89	467
EUROPE	**808**	**87**	**425**	**28**	**47**	**42**	**266**	**895**

The overall spatial distribution of the premature deaths is similar for the different health endpoints. COPD (*Figure 3.8c*), LC (*Figure 3.8d*) and LRI (*Figure 3.8e*) are the causes with lower and less extended mortality over the domain with (< 1 case of premature death per km^2). COPD totalizes 9,000 premature deaths in Western and Central Europe; and 10,000 over Eastern Europe. For LC, 14,000 premature deaths are estimated over Western Europe, 16,000 over Central Europe and 17,000 over Eastern Europe. Last, LRI totalizes 12,000 premature deaths over Western Europe, 11,000 over Central Europe and 19,000 over Eastern Europe. Central Europe is the area where the highest number of cases per grid cell was found; this is the case for Benelux, the Southern UK, Western Germany and some hotspot located in large urban areas. This reflects the combination of high PM2.5 levels and high population density. For the CEV distribution (*Figure 3.8a*), 8,000 deaths are estimated in Western Europe, 24,000 over Central Europe and 55,000 over Eastern Europe (in addition to the aforementioned areas for Central Europe, some more zones in Eastern Europe, as Czech Republic, Slovakia or Hungary, present more than 1 mortality case per km^2).

Conversely, IHD (*Figure 3.8b*) (43,000; 105,000 and 277,000 deaths in Western, Central and Eastern Europe) and all causes of premature deaths (*Figure 3.8f*) (175,000; 253,000 and 467,000 total deaths in Western, Central and Eastern Europe, respectively) affect the whole domain, being their effects higher in Eastern Europe and some hotspots located in large European cities. For IHD and All causes, > 6 premature deaths/km^2 and > 10 premature deaths/km^2, respectively, were obtained. The spatial distribution of the mortality cases across Europe is quite similar to that estimated by Lelieveld et al. (2019) using the same methodology. These authors estimated a total of 790,000 premature deaths over

Europe; while Burnett et al. (2018) estimated 647,000 premature deaths. These numbers are slightly lower than the 895,000 deaths presented in this study (+12% and +27% deaths in this work when compared to Lelieveld et al., 2019 and Burnett et al., 2018; respectively). These differences can be ascribed to a number of factors, namely: the size of the domain, the population used in this work, the higher modelling resolution with respect to previous works (which makes concentration in urban areas higher than that in the aforementioned contributions), different modelling setup, etc.

The distribution of all mortality endpoints follows the same pattern in Europe as in the previous studies, with the highest number of cases over Eastern and Central domains, in particular in the Benelux area. Also, several hotspots can be found in some European megacities as Madrid, Paris or Moscow. Northern Europe (Norway, Sweden and Finland) is the area with the lowest number of cases for all the diseases covered in this work.

Summarizing, Eastern Europe is the largest region and also the region where more cases of mortality for all the causes studied were estimated (*Table 3.3* and *Figure 3.8*). The IHD is the pathology causing the highest number of premature deaths (277,000) in Eastern Europe. Over this area, COPD is the endpoint with the lower number of premature deaths (10,000). A similar pattern is seen for Central Europe (the smallest region in terms of population), where IHD leads the number of premature deaths (105,000) and conversely COPD is the pathology with the lowest incidence (9,000). For Western Europe, the most noticeable difference is that the lowest number of mortality cases are linked to CEV (8,000 deaths). Western Europe is the area where the lower number of mortality cases is found (20% of the total mortality, comparing with the 28% of central Europe or the 52% of Eastern Europe).

Figure 3.9 (left) displays the percentage for each mortality cause for the present-day conditions as a total for Europe. 47% of the mortality cases are due to IHD (425,000 cases); being the pathology with the highest impact on total premature deaths. On the other hand, the cause with the lowest number of deaths is COPD (28,000), which is about 3% of the total mortality associated to PM2.5 in Europe. As commented before, these numbers are slightly higher than those by Lelieveld et al. (2019), who accounted 64,000 CEV deaths (87,000 in this contribution,

+10%) and 313,000 IHD (425,000 here, +47%). Hence, the main cause of mortality in Europe associated with PM2.5 exposure are cardiovascular diseases (IHD+CEV), representing 57% of the total premature deaths. Other NCDs are also important, since they represent 30% of the total mortality (266,000 premature deaths). *Figure 3.9 (left)* also reveals that LC and LRI represent, each one, a 5% of mortality causes (42,000 premature deaths), and COPD adds just 3% (28,000 deaths).

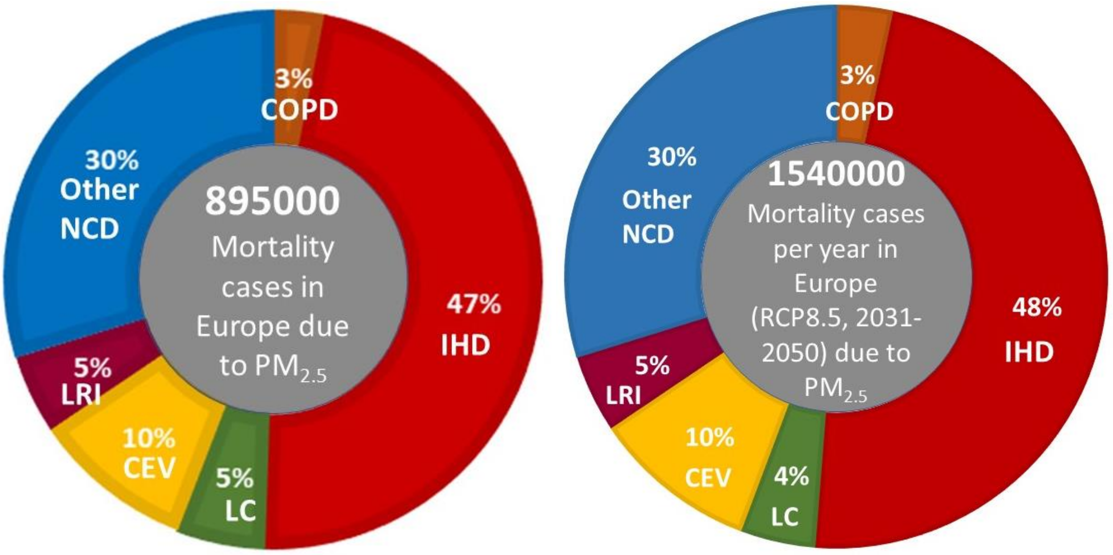

Figure 3.9: *Percentages of premature mortality by disease in Europe for the present period (1991-2010, left) and future RCP8.5 scenario (2031-2050).*

3.3.3 Future (2031-2050, RC8.5 scenario) PM2.5 premature mortality for Europe

The relationship between PM2.5 concentration in Europe and the different mortality causes when changing climate (RCP8.5 scenario) and population distribution was analysed in this section. Overall, the number of premature deaths caused by PM2.5 will increase across all of Europe to in total 1,540,000 (+72% compared to present estimation of 895,000 premature deaths). The results also show that the percentual distribution of each disease will keep barely altered in the future RCP8.5 scenario (*Figure 3.9, right*), so the discussion conducted previously is valid also for the future scenario.

As seen in *Figure 3.10*, the different endpoints of increased premature mortality are located over populated areas with a high concentration of PM2.5. These areas match large European cities, Central Europe (mainly Benelux and Germany) and Eastern Europe.

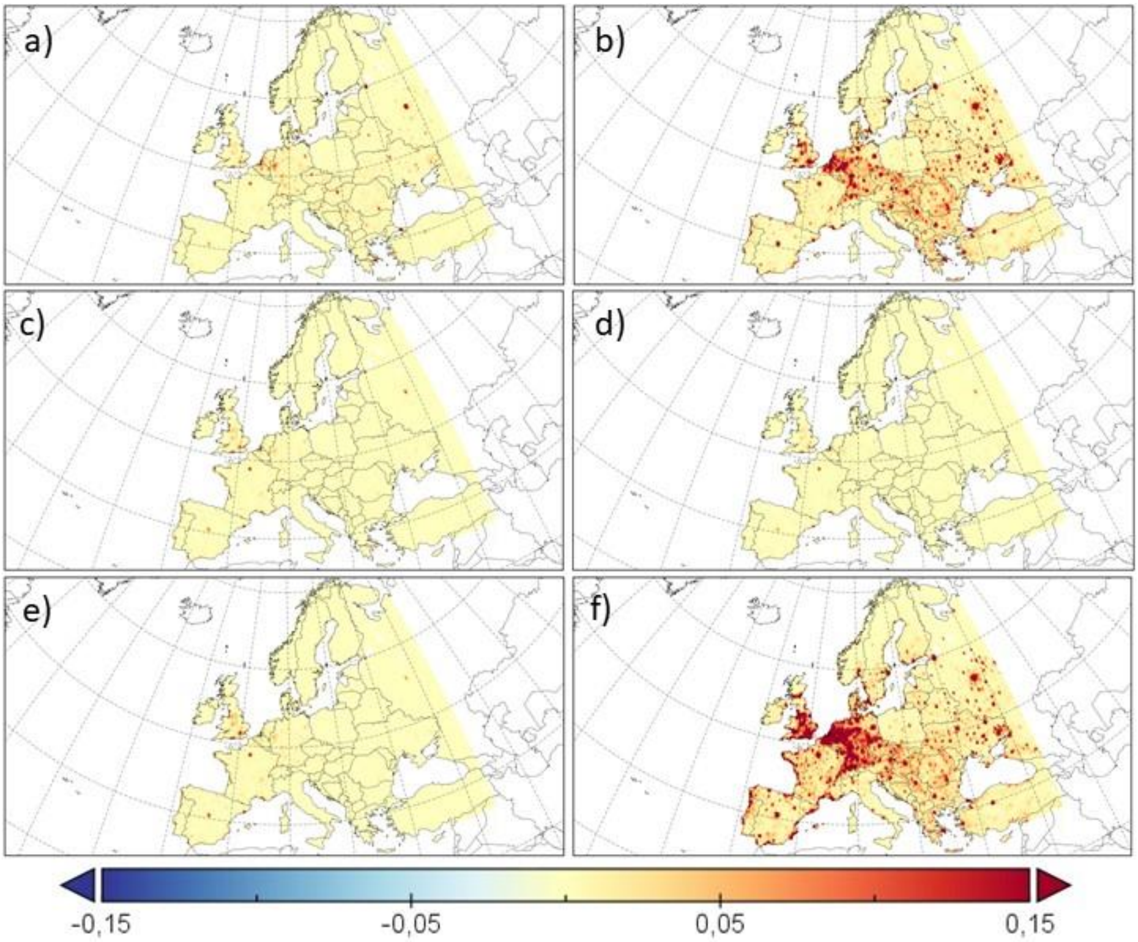

Figure 3.10: *Differences between future (RCP8.5, 2031-2050) and present (1991-2010) premature mortality in Europe (premature deaths/km^2) in both simulations. a) CEV, b) IHD, c) COPD, d) LC, e) LRI and f) All causes.*

The increase on the mortality number in the future (*Table 3.4*) can be ascribed to the increase of the PM2.5 concentration for the RCP8.5 scenario in southern countries together with the aging of the population (previously shown in *Figure 3.2*).

Elderly people are more sensitive to air pollution, which will result in a large increase of the mortality in the future compared to present cases. Silva et al. (2016) detected a decrease in the number of mortality cases for a future RCP8.5 scenario in Europe for the year 2100 in around 150,000 deaths less that for the present period (2000). However, in Silva et al.'s work, Europe was not divided into regions and a similar y_0 for the baseline mortality was implemented for the entire domain. Hence, the differences between this previous work and the current, could be explained by e.g. the use of the same baseline mortality for all Europe by Silva et al. (2016), a different reference year or because they did not take into account the projections and variation in the future population.

Over Western Europe, *Figure 3.10* shows an increase of the mortality in the future scenario when pollution and population increase. On the other hand, although a decrease of the pollution over Central Europe is expected, an important aging of the population is projected by the UN in this area, together with an increase of population living in urban areas, which will lead to an increase in mortality associated to air pollution.

The opposite behaviour occurs over the Eastern region, where the population will decrease and the pollutant concentration will increase, resulting in an increase of the mortality cases.

Table 3.4: *Estimation of annual premature mortality by disease for present (1991-2010) and future (RCP8.5, 2031-2050) periods (in thousands).*

	CEV ($x10^3$)		**IHD ($x10^3$)**		**COPD ($x10^3$)**		**LC ($x10^3$)**		**LRI ($x10^3$)**		**All ($x10^3$)**	
Age	Pres.	Fut.	Pres.	Fut.	Pres.	Fut.	Pres.	Fut.	Pres.	Fut.	Pres.	Fut.
25-29	0.2	0.2	0.8	0.6	0.0	0.0	0.0	0.0	0.6	0.4	4.4	3.2
30-34	0.5	0.4	1.8	1.5	0.0	0.0	0.1	0.1	1.1	0.9	8.0	6.4
35-39	0.8	0.7	3.6	3.1	0.1	0.1	0.2	0.2	1.5	1.3	13	11
40-44	1.4	1.2	6.3	5.5	0.1	0.1	0.6	0.5	1.7	1.5	18	16
45-49	2.3	1.8	12	9.0	0.3	0.2	1.5	1.2	2.1	1.6	28	22
50-54	3.7	2.9	20	16.0	0.6	0.5	3.2	2.7	2.6	2.0	44	34
55-59	5.3	5.1	29.0	28	1.1	1.1	5.6	5.5	3.0	2.8	61	58
60-64	7.6	10	41	55	2.1	2.6	7.8	10	3.1	4.1	80	103
65-69	8.2	13	40	66	2.5	3.8	7.7	11	2.6	4.0	81	127
70-74	12	17	58	80	4.0	5.5	8.3	11	3.5	4.7	112	154
75-79	13	22	60	102	4.3	7.1	5.6	9.4	3.7	6.1	117	195
80plus	31	77	151	370	13	31	6.8	17	17	41	329	807
TOTAL	**87**	**152**	**425**	**736**	**28**	**52**	**47**	**69**	**42**	**71**	**895**	**1538**

Table 3.4 indicates that all the mortality causes studied follow the same pattern (a significant increase with the age of the group in both the present and future case). LRI keeps a similar number of deaths until the group 80+, at the age in which the number increases considerably. Hence, LRI is strongly dependent on the increase of population in the range 80+, that will increase from 4% in the

present period to 9% in the future projects. LRI increases from 42,000 to 71,000 deaths in the future RCP8.5 scenario.

Also, LC results are to be highlighted (48,000 annual deaths in the present vs. 69,000 premature deaths per year associated with air pollution in the future scenario). For this pathology, 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 on mortality are not immediate, as in other causes studied such as IHD or CEV. Henceforth, people affected by lung cancer at such advanced age may die from another cause instead of LC.

Finally, it is also noteworthy that death cases from 25 until 60 years decreases in the future for all mortality causes studied. From 60 years old, mortality increases in comparison with the present period due to the aging of the population in the future. For this reason, a higher number of deaths is obtained for aged people. As shown in *Figure 3.2* the 60-64-age group, is the largest in the future period and therefore this group also presents the largest number of cases for the future period for people over 45 (*Table 3.4* and *Figure 3.11*).

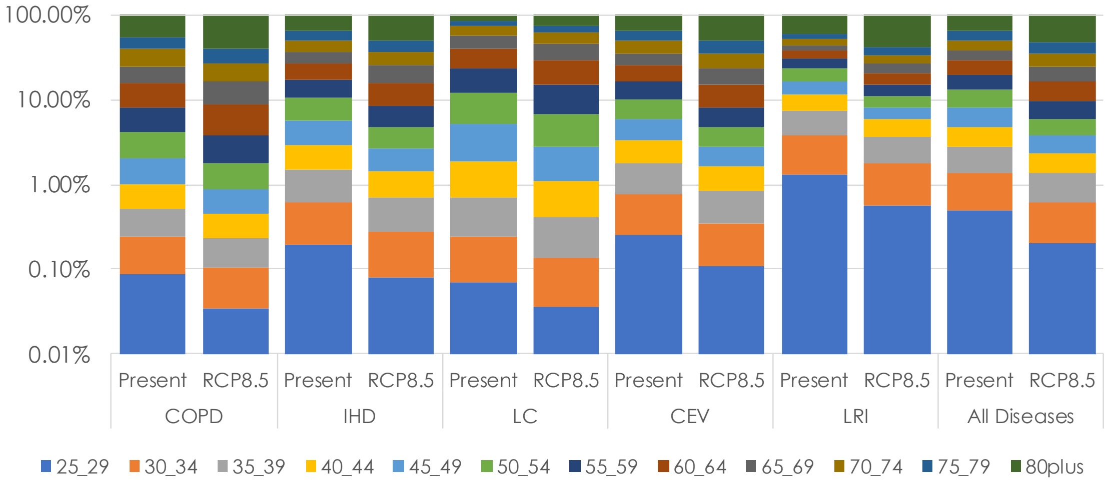

Figure 3.11: *Present (1991-2010) mortality and future (RCP8.5, 2031-2050) estimation of deaths per pathology and age group, shown in %.*

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3.4 Conclusions

The estimation of premature deaths over Europe leads to a total of 895,000 annual premature deaths associated with to air pollution over Europe during the present period (1991-2010). Taking into account future potential the changes in future 1) population according to the UN projections and 2) climate following the RCP8.5 scenario, this number is in the current study projected to increase by 72% for the future period 2031-2050 if the RCP8.5 scenario is considered (1,540,000 premature deaths). This is caused mainly by while the total population for Europe slightly decreases (808 million for present estimations vs. 806 million for 2050s UN-based population).

The most affected areas with highest by mortality due to PM2.5 are large European cities, Central and Eastern Europe. The main causes of mortality in Europe due to PM2.5 are cardiovascular diseases (Ischemic Heart, IHD, and Cerebrovascular Diseases, CEV), representing the 57% of premature mortality over the target area. These pathologies are distributed throughout overspread over the whole domain, in particular IHD. IHD and CEV are more sensitive to the air pollution than the other studied pathologies. In addition, IHD is the pathology leading to the highest number of provoking the largest premature mortality associated to air pollution in Europe, with 425,000 deaths per year during the present period and increasing to 736,000 annual deaths in the future RCP8.5 scenario for 2031-2050 if considering the modifications in the population dynamics due to the aging of European population.

The focus in this contribution has been on the impact from future changes in PM2.5 levels linked to climate changes and in the European population composition. The sensitivity to these parameters is important to understand in order to make improved assessment of future PM2.5 premature mortality. However, the future PM2.5 levels will to a large degree also be driven by changes in the anthropogenic emissions both within and outside Europe. Previous studies (typically with a lower resolution in the applied models) have shown that the expected decrease in European emissions will lead to an overall decrease in the PM levels across Europe and that the impact from climate change alone is less important (e.g. Cholakian et al., 2019; Doherty et al., 2017). In terms of health impact, Geels et al. (2015) found a large decrease in the future number of premature deaths in Europe due to emissions changes following the RCP4.5 scenario.

The methodological approach used in this contribution (using detailed information about baseline mortality coming from regional European information) can help providing a more consistent approach to the estimation of air pollution-derived health issues in each European region, since the different baseline mortality takes into account different socio-economical and climatic conditions from each region. The findings presented here underline the importance of a continued focus on regulation of air pollution as both climate change and the ageing population potentially will counteract benefits of air pollution policies.

Chapter 4

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

Since the industrial revolution, worldwide air quality has worsened as a consequence of increased anthropogenic emissions, in particular from the sector of energy production. The evidence of the effects of this atmospheric pollution in general (and fine particulate matter, PM2.5, in particular) on human health is unquestionable nowadays, producing mainly cardiovascular and respiratory diseases, morbidity and even mortality. These effects can even enhance under a changing climate as a consequence of climate penalties and future changes in the dynamics of population. Because of all these reasons, the main objective of this contribution is the estimation of annual premature deaths (PD) associated to PM2.5 on present and future European population by using non-linear exposure-response functions. Endpoints considered include 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 NDC) on present (1991-2010) and future (2030-2050) periods. PM2.5 concentrations come from simulations running the WRF-Chem chemistry-climate coupled model under present and RCP8.5 future scenario. The cases assessed include the estimation of present PD (PRE-P2010), the quantification of the role of a changing climate on PD, with population constant at 2010 levels (FUT-P2010) and the importance of population dynamics projected for the year 2050 on PD (FUT-P2050). Two additional cases (REN80-P2010 and REN80-P2050) evaluate the impact on premature mortality 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 annual PD over Europe, with IHD being the largest contributor to premature mortality in both present and future scenarios. The case isolating the effects climate penalty (FUT-P2010) on air quality estimates a variation +0.2% of PD over the whole domain. However, under this scenario 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 modification of population dynamics (FUT-P2050) will lead to a large increase of annual PD (1,540,000 PD per year, +71.96% with respect to PRE-P2010 and +71.67% to FUT-P2010) principally 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 annual PD for the year 2050 (a decrease of -4% in comparison with the no-mitigation scenario, FUT-P2050). In spite of the limitations of this work due to uncertain future estimations, this work reveals the need of the governments and public entities to take action and bet for mitigation policies

4.1 Introduction

Air pollution is nowadays a leading cause of global disease burden, especially in countries with 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 particulate matter (PM) 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 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, (World Health Organization, 2013)); 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. Focussing on Europe for present scenarios, Lelieveld et al. (2013) calculate global respiratory mortality 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 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) PD are related to PM2.5 since the preindustrial era. In addition, this 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 local emissions of short-lived air pollutants and their precursors. The main source of emission 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).

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 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 number of mortality cases. 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 life expectancy from air pollution.

Hence, the objective of this study is to estimate the present (1991-2010) annual PD 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 renewable 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 NDC) is included in this contribution.

4.2 Methodology

4.2.1 Premature mortality estimation by exposure-response functions

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 3.1*) to estimate premature mortality. This equation is based on epidemiological relationships between air pollution concentration and mortality in each grid 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 3.1*) and is estimated by the WHO for each sex and every year. Sex mixing values (including both male and female) during the year 2017 (the last available) were chosen for this study. Premature mortality and RRs has been estimated for each pathology and different group ages included in this 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 3.3*). Where θ, α, μ and v 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 Disease (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.

4.2.2 Population data

Population data for Europe has been taken from the NASA SocioEconomic Data and Applications Center (2019) gridded 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 km^2. Population data were interpolated to the working grid to make it consistent with the gridded air pollution data (*Figure 3.3 top*).

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 Dynamics (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 3.3 bottom*). The population pyramid both for the year 2010 and 2050 is presented in *Figure 3.2*. This Figure indicates a very slight projected decrease (-0.2%) of European population (807.5 M vs. 806.2 M dwellers both for present 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.

4.2.3 Air quality data and scenarios

The availability of 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 misalignment 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).

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 3.3* 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 supposes an upper limit to climate impacts (Moss et al., 2010). The reference periods span 1991-2010 for the present and 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 in air quality levels.

The parameterizations implemented in the WRF-Chem model, together with the model data used for these simulations, has 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 3.1*.

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 achievable if the power sector is assumed to implement essentially carbon-free technologies, and hence that emission scenario (from 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 4.1*). 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%); solar power (23%); biomass and hydropower (12% each); and geothermal, which presents the smallest contribution in 2050 (2%). *Figure 4.1* 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 4.1*.

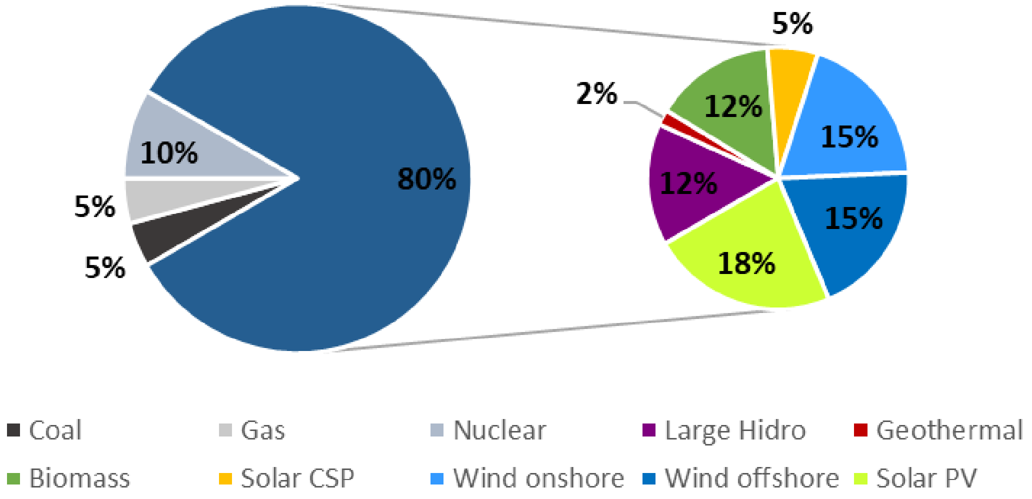

Figure 4.1: *Energy mix in the REN80 scenario for the year 2050.*

Table 4.1: *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 × 10^9	%	GJ × 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%	–	–

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, 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 4.2* 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 11,640 g/GJ, respectively), while oil is the most important contributor (per GJ of energy produced) in the case of particulate matter PM10 and PM2.5 (923 g/GJ and 798 g/GJ, in that order) and non-methane volatile organic compounds (436 g/GJ).

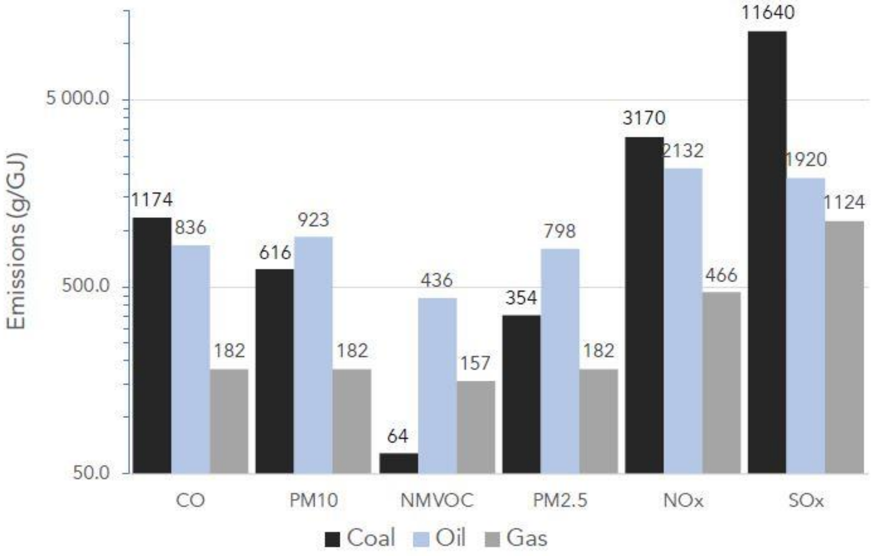

Figure 5.2.2.12: *Emission factors (g/GJ) by different type of fuel.*

Finally, present and future emissions from the energy sector were estimated following the European Environment Agency (2019) methodology (*Equation 4.1*) from the energy produced by each type of fuel and the corresponding emission factor:

$$Emissions = Activity\ Factor\ (GJ) \times Emission\ Factor\ (g/GJ) \tag{4.1}$$

The annual mass of pollutants emitted by the different fuels included here (coal and lignite, oil and gas) is shown in *Table 4.2*. 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 4.2:** Present and future annual emissions of regulatory air pollutants produced by the energy sector used in the simulations (in Mtons).*

	Present (1991-2010)	Future (2031-2050)	∆Emissions
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%

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

Table 4.3 compiles the different cases that have been included in this contribution for the estimation of PD associated to PM2.5 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 dynamical 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 pollutants for the future RCP8.5 scenario using REN80 emissions and with population corresponding to the year 2010 and changes for 2050, respectively.

***Table 4.3:** 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)

4.3 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 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 for the future case considering also the change on the population dynamics (2050 population) (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.

4.3.1 Levels of PM2.5 in present and future scenarios

Figure 4.3 shows the PM2.5 mean annual concentration over Europe for the present period (1991-2010) the changes projected in the future scenario (2031-2050, RCP8.5) both with emissions from ACCMIP and in the mitigation scenario (2031-2050, RCP8.5 +80% renewables energies scenario, 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 established by the European Directive 2008/50/EC on ambient air quality and cleaner air for Europe (25 μg m−3). For the present period, eastern Europe and some large conurbations have the highest concentrations of fine particles, with some cities as Paris (France), Krakow (Poland), Moscow (Russia) presenting elevated levels and exceeding 25 μg m^{-3}, limit value of the European directive.

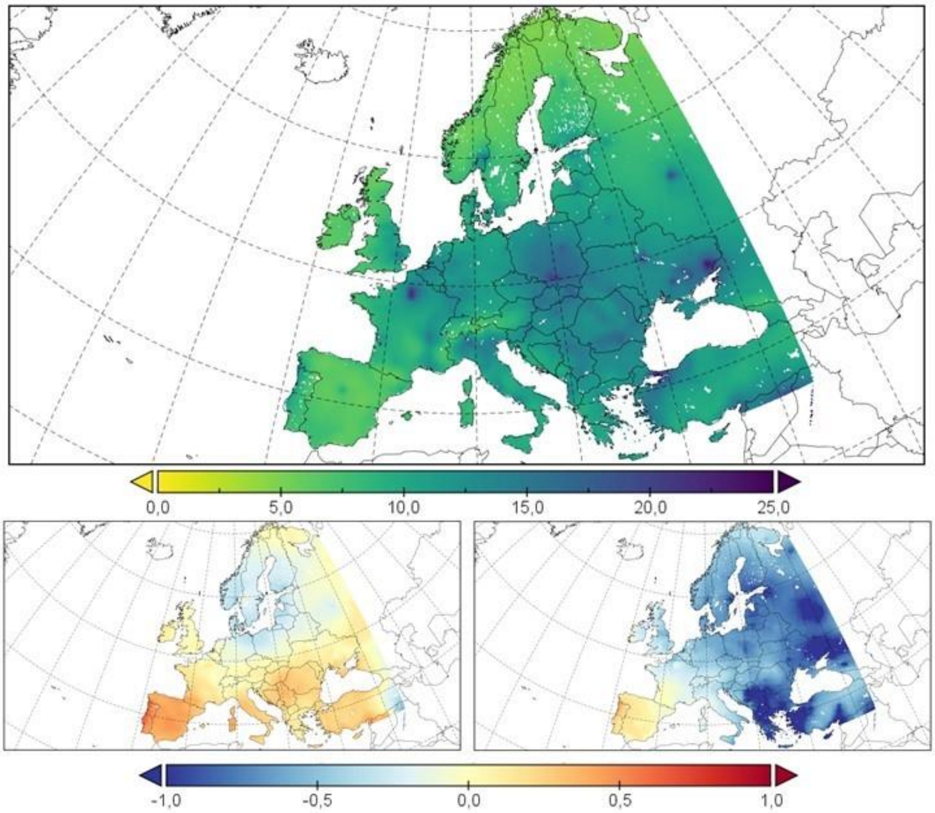

Figure 4.3: *PM2.5 concentration over Europe for (top) present period (1991-2010); (bottom-left) difference with the future scenario (2031- 2050, RCP8.5); and (bottom-right) difference with the future (2031-2050, RCP8.5) +80% renewables energies scenario (REN80).*

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 particulate matter over this area betting for renewables area can be of 0.5 μg m^{-3} more of PM2.5. 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 scenario of 80% of energy production through renewables sources (REN80) 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 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 be benefit both from climate penalty and from the mitigation scenario. This benefit 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 since the enhancement of fine particles concentrations as a consequence of decreasing precipitations and increased emissions from natural sources (Jiménez-Guerrero et al., 2013b) (*Figure 4.3*).

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

Figure 4.4 depicts the annual PD associated to the present case PM2.5 pollution (PRE-P2010). For the present period (1991- 2010), 895,000 annual PD are estimated over the European, in agreement with the results of Andersson et al. (2009) and Crippa et al. (2019). The higher number of annual PD are estimated for Eastern Europe (467,000 PD) (*Table 4.4*), while the highest number of PD per 100,000 adult inhabitants are found over Central Europe (229.4 PD/100,000 habitats). This latter result is in agreement with whose results by Silva et al. (2016a), who identify the Benelux as the most affected region by PD over the entire European domain.

Table 4.4: *Estimated annual premature deaths (PD, in thousands) and PD per 100,000 habitants for each European region in all scenarios covered.*

	Present	PRE-P2010	RCP8.5	FUT-P2010	RCP8.5	REN80-P2010	RCP8.5	FUT-P2050	RCP8.5	REN80-P2050
	PD × 10^3	PD/100,000 h.	PD × 10^3	PD/100,000 h.	PD × 10^3	PD/100,000 h.	PD × 10^3	PD/100,000 h.	PD × 10^3	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
Central EU	252.7	229.4	250.7	227.6	244.3	221.8	448.2	372.5	437.5	363.6
Eastern EU	466.7	167.3	467.9	167.7	444.8	159.5	759.9	262.0	723.6	249.4
EUROPE	894.3	167.5	895.8	157.8	861.5	151.8	1535.4	253.9	1479.3	244.7

(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.

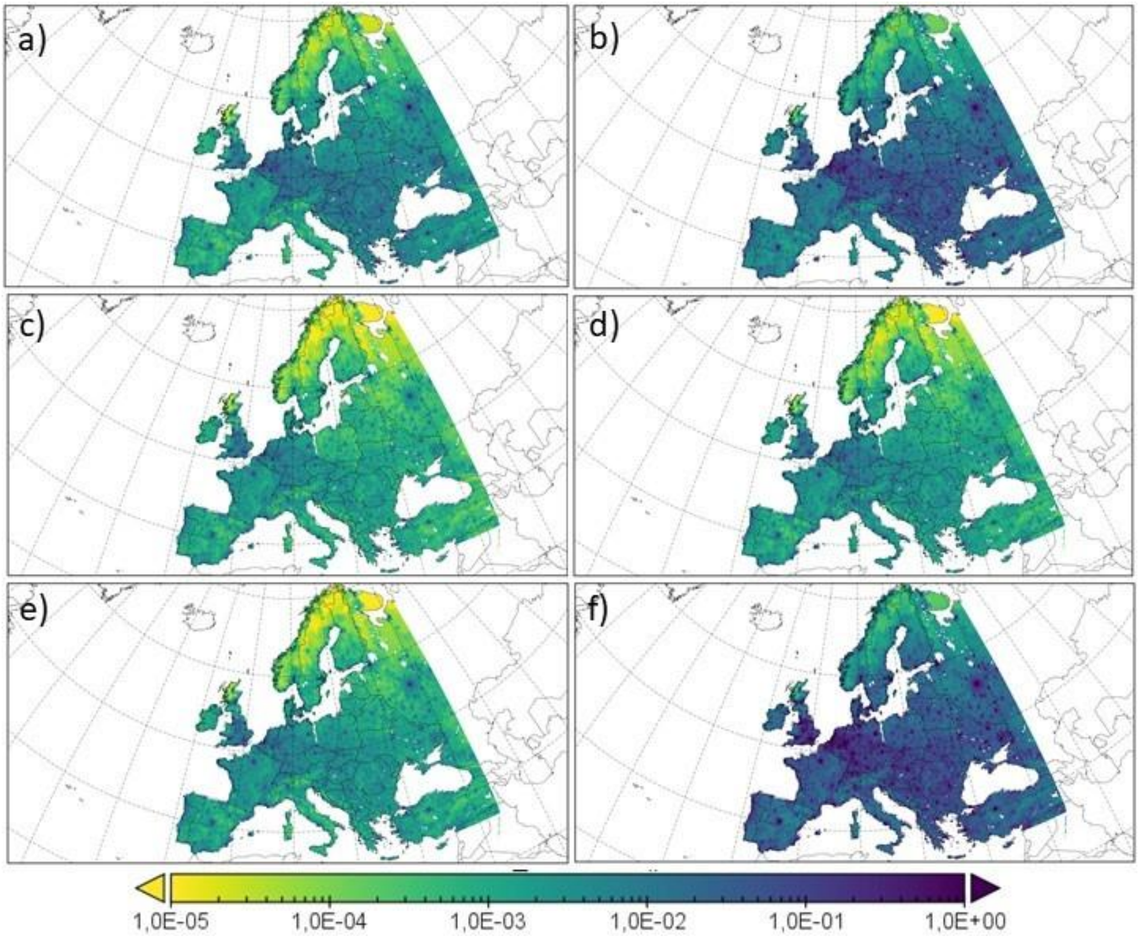

Figure 4.4: *Estimation of PD over Europe for the PRE-P2010 case for different endpoints: (a) CEV, (b) IHD, (c) COPD, (d) LC, (e) LRI and (f) all. All units are PD/km^2.*

When considering individual endpoints (*Figure 4.5*), the main cause of PD over Europe is related to cardiovascular diseases (IHD+CEV), especially over Eastern Europe. Moreover, CEV and IHD are those with the highest differences between each target area, concentrating Eastern Europe more than 60% of the cases related to these pathologies (*Figure 4.5*) because of the larger population (51% of the total European population contemplated in this contribution), but also because of the higher PM2.5 concentrations (as previously shown in *Figure 4.3*) in comparison with Central (19% of European population) and Western Europe (30% of the European habitants). Those results are analogous for the total PD by all causes: PD are similar (with respect to their percentage) to the population hold in the respective areas. In this sense, Eastern Europe represents more than 50% of mortality in Europe, while Central and Western Europe add around 20 and 30% of PD, proportional to their population.

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).

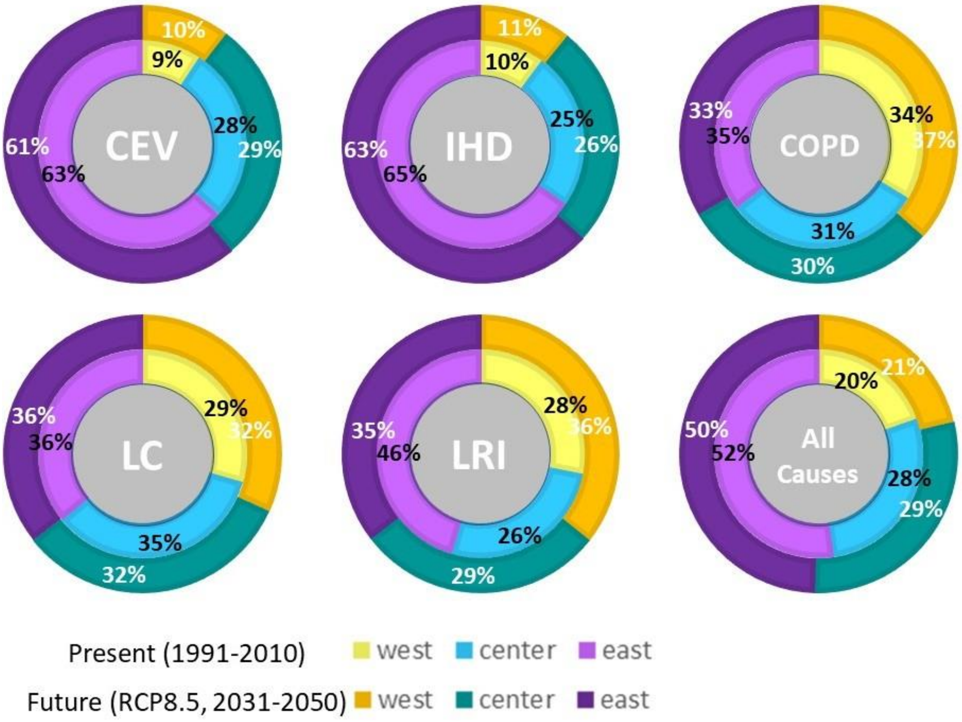

Figure 4.5: *Relative contribution of each cause of PD by European region for the PRE-P2010 and the FUT-P2050.*

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

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) (FUT-P2010 vs. PRE-2010). For that, population has been kept constant at 2010 levels. The results presented in *Table 4.5* indicate that the climate penalty has a very limited impact on future premature deaths over Europe (*Figure 4.6*). When comparing the total 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 among different regions of Europe. While total PD per 100,000 adults (*Table 4.4*) 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 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 4.5: *Estimated annual premature deaths (PD × 10^3) 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 × 10^3	PD/10^5 h.	PD × 10^3	PD/10^5 h.	PD × 10^3	PD/10^5 h.	PD × 10^3	PD/10^5 h.	PD × 10^3	PD/10^5 h.
COPD	27.7	4.9	27.8	4.9	26.5	4.7	52.2	8.6	49.8	8.2
LC	47.6	74.7	47.7	74.8	45.4	71.8	68.7	121.7	65.3	116.8
LRI	42.4	8.4	42.6	8.4	40.0	8.0	71.1	11.4	67.0	10.8
CEV	86.9	15.3	87.1	15.3	81.8	14.4	151.6	25.1	142.4	23.5
IHD	424.1	7.5	424.5	7.5	407.5	7.0	736.0	11.8	706.3	11.1
Other NCD	265.6	46.8	266.2	46.9	260.3	45.9	458.4	75.8	448.5	74.2
All endpoints	894.3	157.5	895.8	157.8	861.5	151.8	1537.9	254.3	1479.3	244.7

(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 pathologies most sensitive to changes in PM2.5 are CEV, but especially IHD (*Figure 4.6*), which is in agreement with 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 cases increase from 424,000 to 425,000 (nearly +3%) 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).

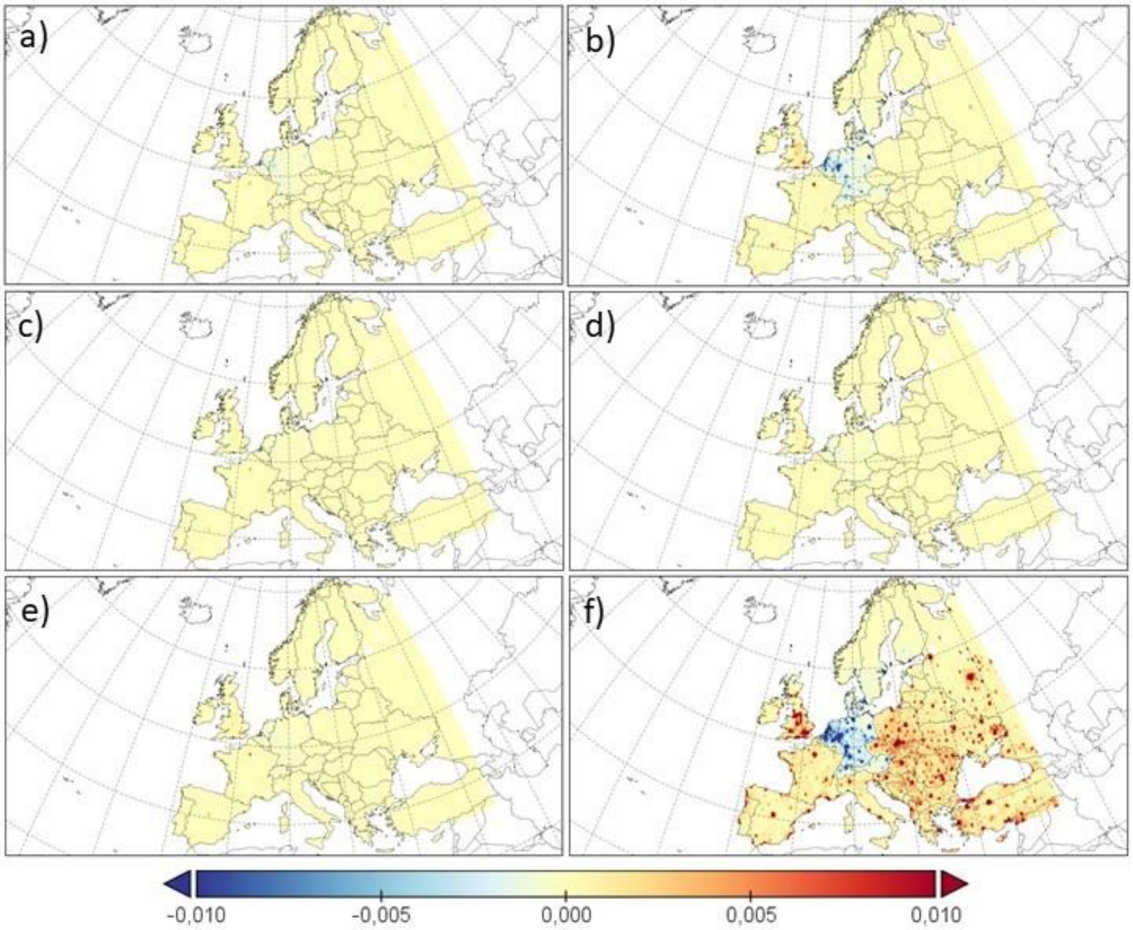

Figure 4.6: *Differences between PD over Europe for the FUT-PRE2010 and the PRE-P2010 case for different endpoints: (a) CEV, (b) IHD, (c) COPD, (d) LC, (e) LRI and (f) all endpoints. All units are PD/km^2.*

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

The previous section analysed the contribution of climate change alone (RCP8.5 scenario, keeping population constant) to PD over Europe. Here, the impact of including the UN 2050 population dynamics in addition to climate change is added. This scenario is denoted as FUT-P2050. As shown in *Figure 4.7* the mortality cases in this projection follow the same pattern that for the future scenario where is take into account the climate change action and the future population, being IHD the cause that present more cases and which is more overspread on the domain. For this case, the projected PD add up to 1,540,000 cases, with Eastern Europe being the most affected region, with almost half of the PD over Europe (*Table 4.4*).

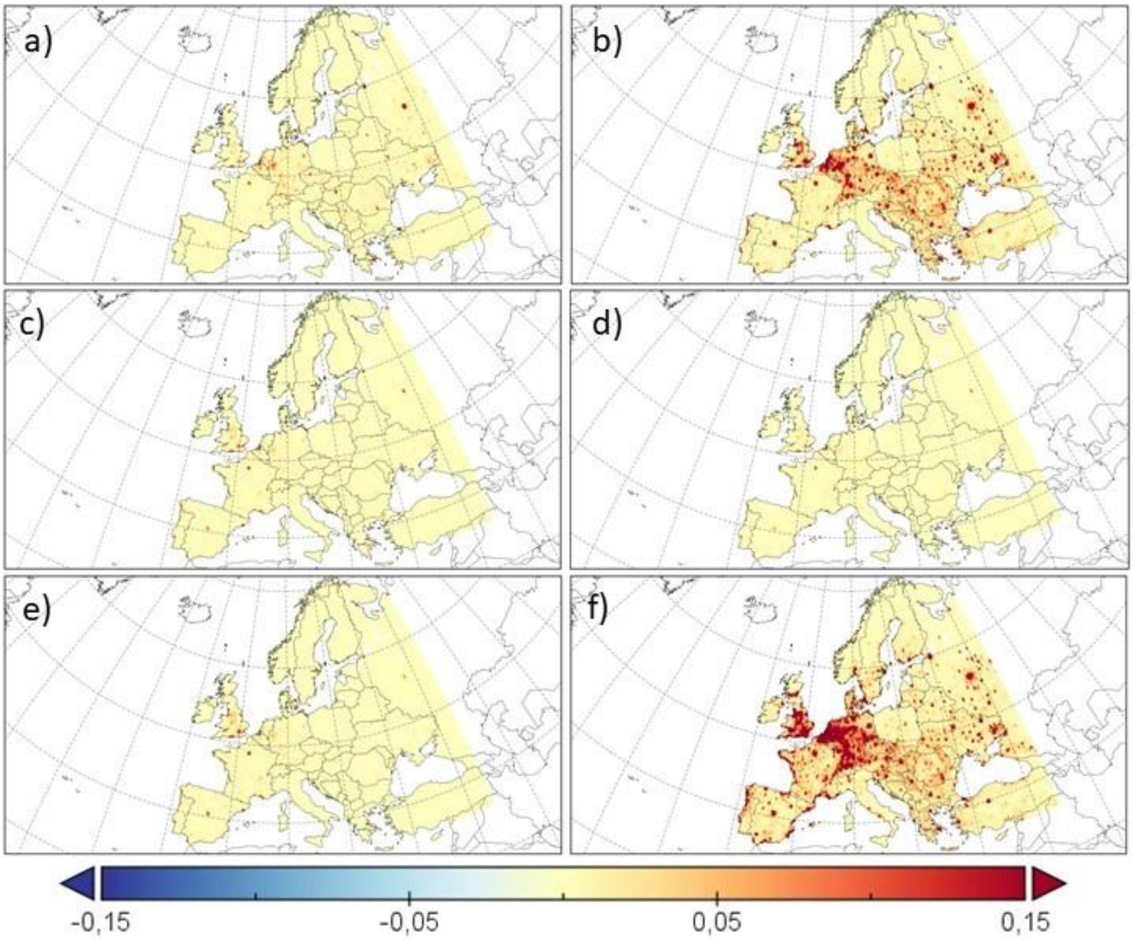

Figure 4.7: *Differences in future premature mortality for the future scenario considering the population dynamics for 2050 (FUT-P2050). Endpoints considered are (a) CEV, (b) IHD, (c) COPD, (d) LC, (e) LRI and (f) All endpoints. All units in PD/km^2.*

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, from 894,000 PD year^{-1} in 1990-2010 to 1,540,000 PD year^{-1} in 2031-2050 (*Table 4.5*). The leading cause of PM2.5-related mortality is IHD for both present and future cases (424,100 PD year^{-1}, which increases by 74%, to 736,000 PD year^{-1}, in the FUT-P2050 case). IHD is followed by Other-NCD, with 265,600 PD year^{-1} increasing by 73%, to 458,400 PD year^{-1} in the FUT-P2050 case.

When assessing the relative contribution of each endpoint to the total PD both in the PRE-P2010 and the FUT-P2050, *Figure 4.5* indicates that future climate change and the modification of population dynamics will barely change the relative percentage of each mortality cause by region, so discussion is analogous to that presented in Section 4.3.2. The only 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).

4.3.5 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 the 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). *Figure 4.8* shows that in the REN80-P2010 scenario, the premature mortality cases will be lower than in the REN80-P2050 scenario, which considers changes on the population dynamics, as previously discussed for the FUT-P2010 and FUT-2050. Larges cities and central Europe are the areas where the number of PD will increase with a changing population in the density and age of population, as previously shown in *Figure 3.2*. A summary of PD in all scenarios is presented in *Table 4.4*.

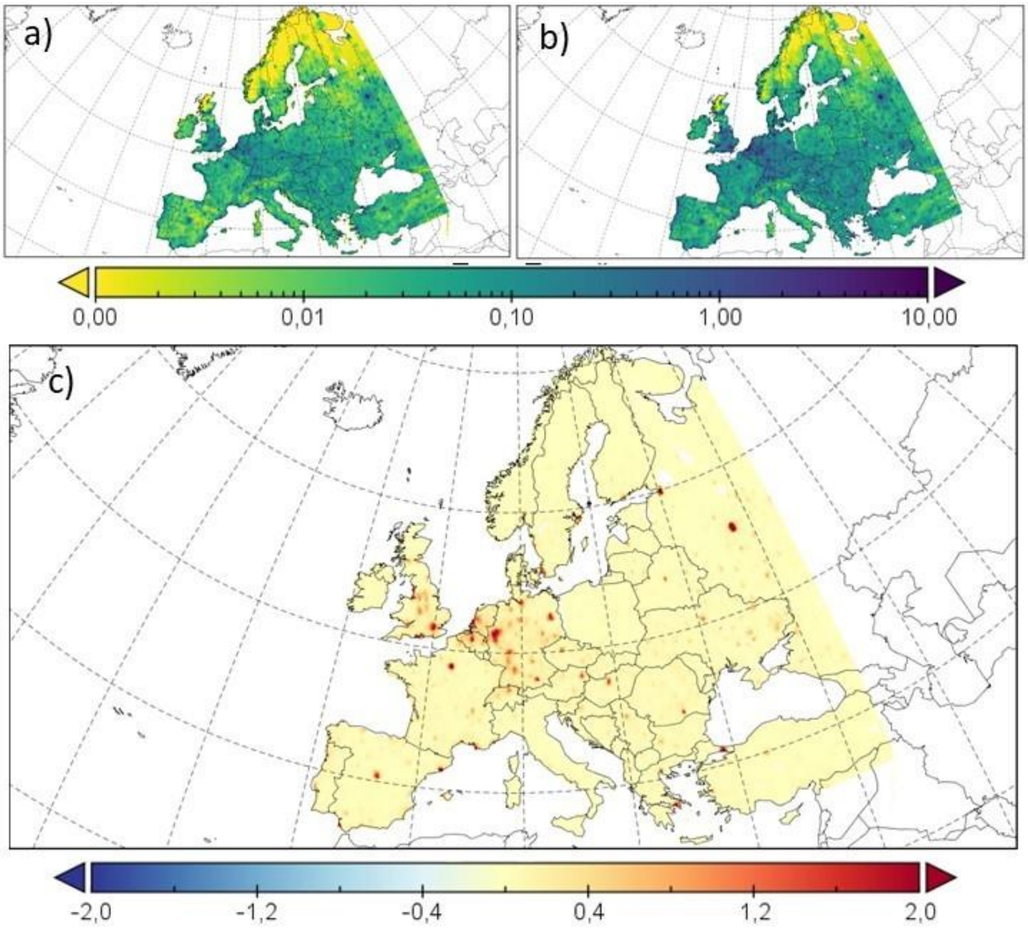

Figure 4.8: *Future (2031-2050) premature deaths for (a) the mitigation scenario keeping constant the present population (REN80-P2010) and (b) mitigation scenario considering the population dynamics for 2050 (REN80-P2050). (c) Differences between both future scenario (REN80-P2050 minus REN80-P2010). All units in PD/km^2.*

The number of all the mortality causes studied decrease on the future mitigation scenario (REN80-P2010 and REN80-P2050) when compared to the corresponding FUT-P2010 and FUT-2050, respectively by 4%. This decrease in especially produced in central and eastern regions regarding the number of total PD (*Table 4.4*). This is explained by the fact that an 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 4.5* indicate that CEV and IHD present the largest relative reductions 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 4.9*), with around -4% cases less for the renewable scenario for LC. Other NCD decreases just by -2% in the renewables case. Other NCD and CEV are the endpoints experiencing the largest improvement in the mitigation scenario, with nearly -

30,000 and -10,000 annual PD, respectively. The lowest difference is displayed by Other NCD representing only 2% of difference and 30,000 cases.

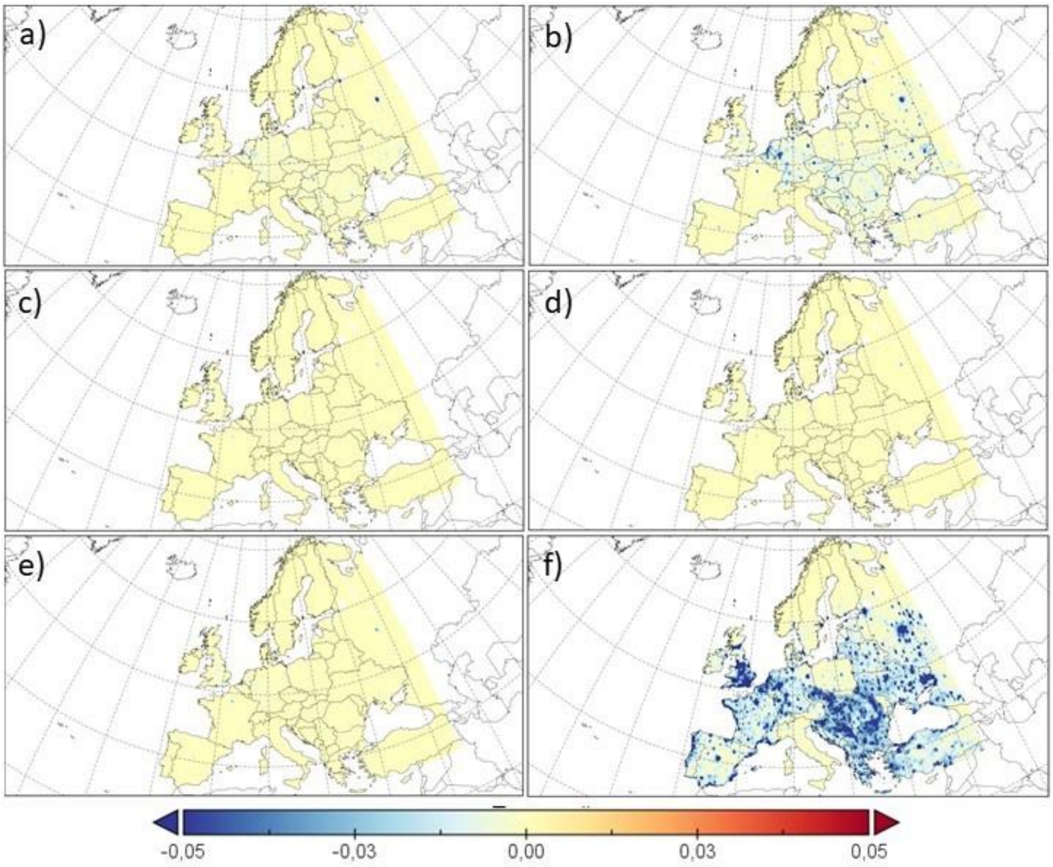

Figure 4.9: *Differences in future premature mortality for the future scenario P2050 and the mitigation scenario (REN80-P2050), both considering the population dynamics for 2050. Endpoints considered are (a) CEV, (b) IHD, (c) COPD, (d) LC, (e) LRI and (f) All endpoints. All units in Premature Deaths (PD) per km^2.*

4.3.6 Effect of the population dynamics

Last, this section tries to shed some light on the effect of the population dynamics and the aging of the European population, as, overall, it should be pointed out that almost half all the PD over Europe occur in the group of 80+. A comparison for the PD for each age group considered among the different future scenarios is shown in *Table 4.6.*

In particular, the effect of the aging 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 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 scenario (*Figure 3.2*). 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 (+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.

Table 4.6: *Estimated annual premature deaths (PD × 10^3) by age range 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
Age Range	PD × 10^3	PD/10^5 h.	PD × 10^3	PD/10^5 h.	PD × 10^3	PD/10^5 h.	PD × 10^3	PD/10^5 h.	PD × 10^3	PD/10^5 h.
25-29	4.4	7.5	4.4	7.5	4.2	7.2	3.2	7.2	3.0	6.9
30-34	8.0	13.8	8.0	13.8	7.7	13.3	6.4	13.6	6.2	13.0
35-39	12.7	22.0	12.7	22.1	12.2	21.1	10.9	22.3	10.5	21.3
40-44	18.0	31.4	18.0	31.5	17.3	30.2	15.7	32.4	15.1	31.1
45-49	28.5	48.0	28.5	48.1	27.4	46.2	21.8	47.6	20.9	45.7
50-54	43.6	77.1	43.6	77.2	41.9	74.2	34.5	75.1	33.1	72.2
55-59	60.8	118.3	60.8	118.5	58.5	113.9	58.4	117.5	56.2	113.0
60-64	80.0	182.5	80.1	182.6	77.0	175.6	103 .4	191.0	99.3	183.4
65-69	80.7	236.9	80.8	237.2	77.8	228.4	126.7	243.8	121.8	234.3
70-74	112.3	328.3	112.5	328.8	108.0	315.7	153.9	321.9	147.7	308.8
75-79	116.8	460.9	117.0	461.8	112.4	443.5	195 .4	458.6	187.6	440.2
80+	328.7	1035.3	329.4	1037.5	317.2	999.3	807 .5	1043.7	778.0	1005.6
TOTAL	894.3	157.5	895.8	157.8	861.5	151.8	1537.9	254.3	1479.3	244.7

(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.

With respect to individual endpoints, LRI keeps a similar number of deaths until the group 80plus, at the age in which the number increases considerably (*Figure 4.10*). Hence, LRI is not strongly sensitive to the aging of population, but to the modifications in number of dwellers. If changing in population is consider, LRI increases from 42,000 in PRE-P2010 to 71,000 PD year^{-1} in the FUT-P2050 case. Also, LC results are to be highlighted (48,000 PD year^{-1} in PRE-P2010 vs. 69,000 PD year^{-1} 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 on mortality is not immediate, as in other endpoints covered such as IHD or CEV.

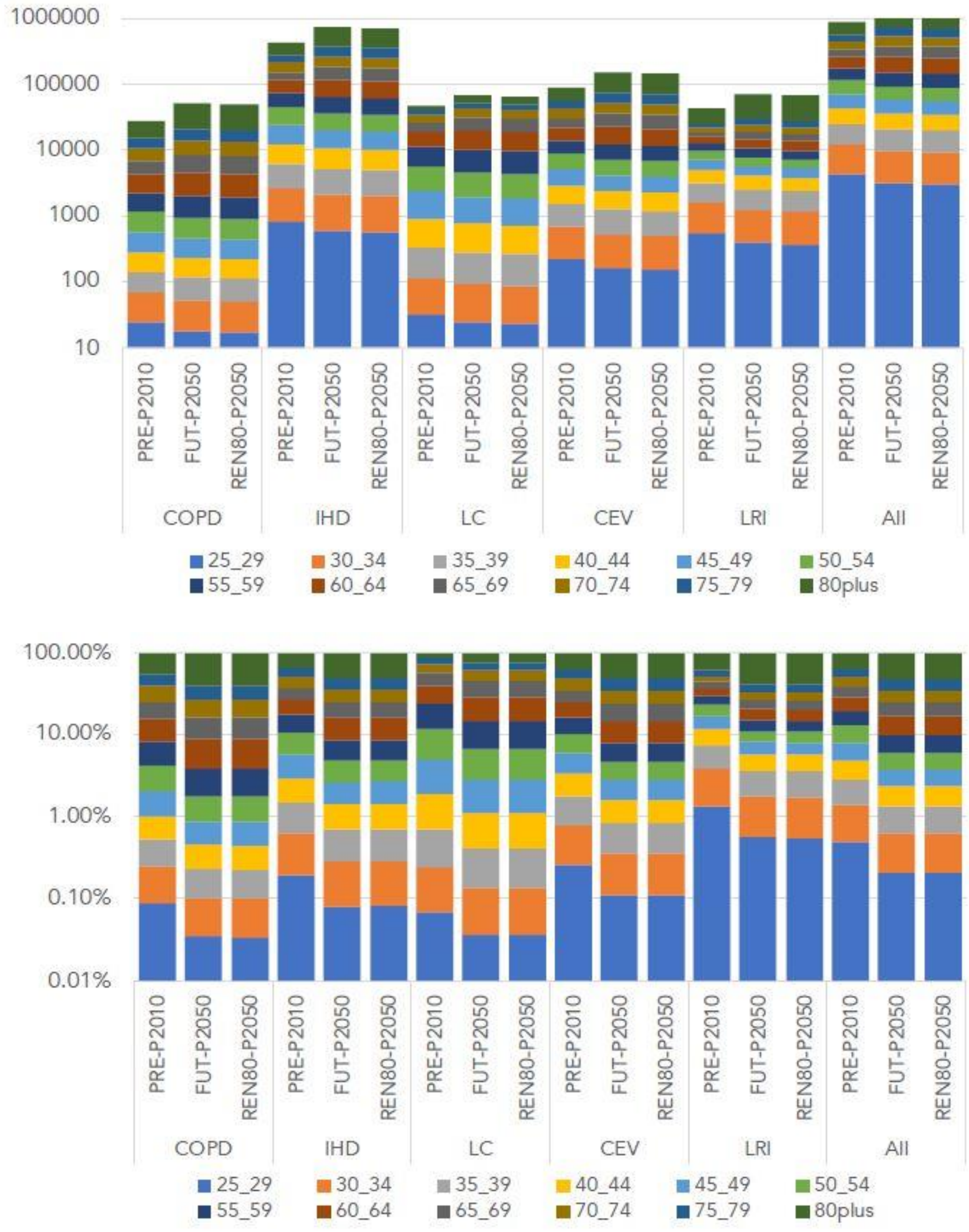

Figure 4.10: *Present (PRE-P2010) and future (FUT-P2010/P2050) estimation of PD per pathology and age group over Europe (top, Total PD per year; bottom, %).*

Henceforth, people affected by lung cancer at such advanced 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 number of deaths is obtained for aged people.

Hence, the differences between PRE-P2010 and FUT-P2010/P2050 must be sought in the differences among the risk ratios estimated by *Equation 3*.3. RRs are higher for younger age groups, with the number of PD higher for older groups, since the baseline values (y0) in *Equation 3.3* are much higher for advanced ages, since aged people presents higher baseline mortality rates than younger dwellers.

4.4 Conclusions

This contribution has included the impacts of atmospheric pollution by fine particles (PM2.5) on premature mortality for different present and future scenarios. The non-linear methodology employed estimated 894,000 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 to 896,000 over the target domain of Europe. Henceforth, 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.) as a consequence in the reduced PM2.5 levels over this latter region under the RCP8.5 due to increased precipitation (*Figure 4.11*). 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.

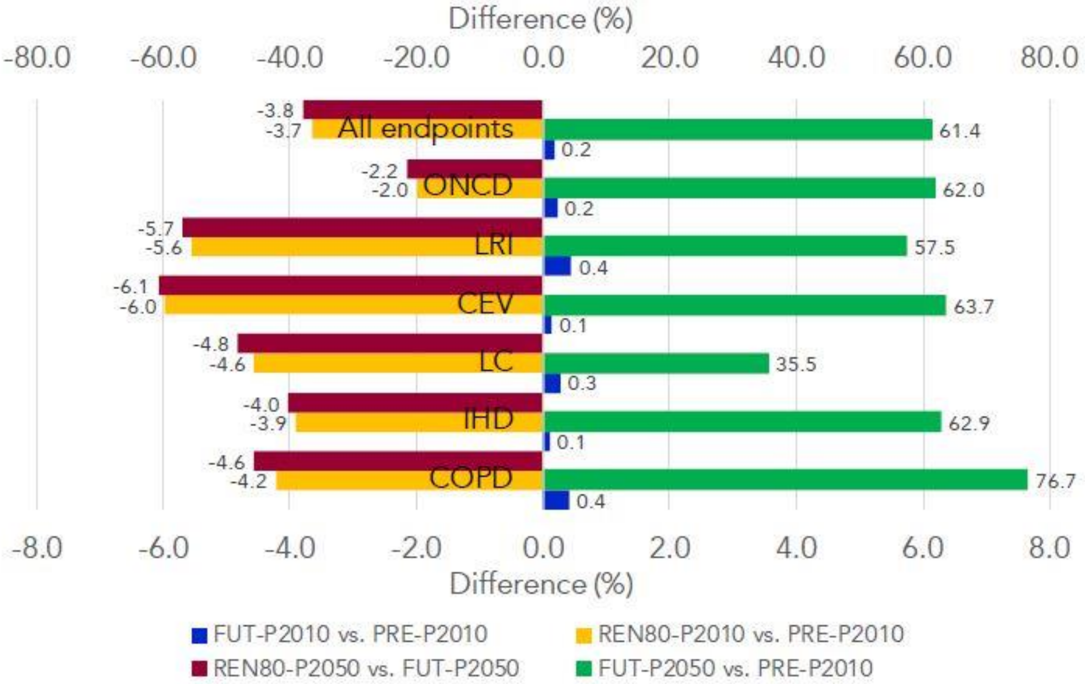

Figure 4.11: *Relative differences for PD/100,000 habitants between the different scenarios for all the endpoints included in this work. FUT- P2010, FUT-P2050 and REN80-P2010 have been compared to the PRE-P2010 scenario, while the differences of the REN80-P2050 scenarios are estimated with respect to the FUT-P2050 scenario.*

2. Impact of changes in population dynamics: this modification, together with the action of climate change (FUT-P2050), the premature mortality expected is 1,540,000 annual PD (an increase of 71.96% with respect to the present scenario and 71.67% to the future scenario in which only the action of climate change is considered). In contrast to the scenario in which population is invariable (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 annual PD in the year 2050 (1,480,000 cases 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 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 most important cause of mortality over Europe (over 50% of total premature mortality), with ~ 424,000 annual PD in the present and the climate penalty scenario. When the change in population dynamics is considered, 736,000 annual PD are associated to this endpoint. This number and reduces by -30,000 annual PD when the mitigation by renewables energy is considered. These results are caused by the high sensitivity of IHD to PM2.5. The second most important cause is CEV, with a ~ 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 some added value with respect to previous contributions. For instance, different baseline information has been included depending on the area of Europe considered. In addition, the PD by age-range have 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 over the European domain.

Last, it should be born in mind that these results are estimated for different future cases and scenarios. Henceforth, these number are associated to different variables that sometimes are hard 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 action and clearly implement mitigation policies, which could improve air quality and therefore, the wellness of the European citizens.

Chapter 5

Impact of extreme wildfires on PM10 levels and human mortality in Portugal

Uncontrolled wildfires have a substantial impact on the environment, the economy and local populations. According to the European Forest Fire Information System (EFFIS), between 2000 and 2013 wildfires burnt about 170,000-740,000 ha of land annually on the south of Europe (Portugal, Spain, Italy, Greece and France). Although most southern European countries have been impacted by wildfires in the last decades, Portugal was the most affected, having the highest percentage of burned area comparing to its whole territory. For this reason, it deserves a closer attention. However, there is a lack of knowledge regarding the impacts of the wildfire-related pollutants on the mortality of the population. All wildfires occurring during the fire seasons (June-July-August-September) from 2001 and 2016 were identified and those with a burned area above 1000 ha were considered for the study. To assess the spatial impact of the wildfires, these were correlated with PM10 concentrations measured at nearby background air quality monitoring stations, provided by the Portuguese Environment Agency (APA). Associations between PM10 and all-cause (excluding injuries, poisoning and external causes) and cause-specific mortality (circulatory and respiratory), provided by Statistics Portugal, were studied for the affected populations, using Poisson regression models. During the studied period (2001-2016), more than 2 million ha of forest were burned in mainland Portugal and the 48% of wildfires occurred were large fires. A significant correlation between burned area and PM10 have been found in some NUTS III (regions) on Portugal, as well as a significant correlation between burned area and mortality. North, centre and inland of Portugal are the most affected areas. The high temperatures and long episodes of drought expected on the future will increase the probabilities of extreme events and therefore, the occurrence of wildfires.

5.1 Introduction

The existence of wildfires constitutes a considerable impact on the environment and humans living in numerous regions worldwide. Climate change has lately been identified as a very important variable to be considered in this matter and global warming scenarios are forecasting an increase of the number and intensity of wildfires during the next years (Bowman et al., 2017). Global warming will produce changes in temperature and precipitation patterns which will increase the prevalence and severity of wildfires (Settele et al., 2014), consequently impacting future air quality (Schar et al., 2004). In fact, an increase on the number of droughts, heat waves and dry spells is suggested by climate change projections, which could not only extend the burnt area in chronically impacted areas, but also affect new ones (Gillett et al., 2004), as was the case of Sweden in the summer of 2018 (Lidskog et al., 2019). One of the areas of the world most fustigated by wildfires is the Mediterranean basin (Portugal being the most impacted country), which needs to be studied carefully to address the concerns of local populations.

Although there has been a slight decreasing trend in the burnt area in this region since 2000 after an increasing period in the previous 20 years (EEA, 2019), recent extreme events like the 2017 fires in Portugal and the 2018 fires in Greece which even resulted in a severe loss of human lives are confirming the worst projections. In fact, a recent study by Turco et al. (2019) showed a relationship between drought and the occurrence of wildfires and suggested an increase of both due to future climate change. But already some years before, the PESETA (Projection of Economic impacts of climate change in Sectors of the EU based on bottom-up Analysis) study estimated an increase of the burnt area in southern Europe in the future (Ciscar et al., 2014).

Uncontrolled wildfires emit numerous pollutants derived from the incomplete combustion of biomass fuel, which cause damage to human health, particularly the respiratory system (WHO, 2010). Examples include particulate matter (PM), carbon monoxide, methane, nitrous oxide, nitrogen oxides, volatile organic compounds (VOCs), and other secondary pollutants (Cascio, 2018) that are released mainly into the atmosphere but can be transported to many other environmental compartments. Moreover, they can affect the physicochemical properties of the atmosphere, as for instance the interaction of PM with solar radiation which can prompt a modification of the temperature depending on the characteristics of the aerosol (Trentmann et al., 2005). Consequently, some of these chemicals are regulated by the European Directive 2008/50/EC of 21 May 2008 of the European Parliament and of the Council on Ambient Air Quality and Cleaner Air for Europe, which establishes threshold values for a safe air quality. But although wildfire emissions are a crucial parameter for the local air quality (IPCC, 2007), where in some cases there are already chronically-exposed populations due to the frequency and dimension of the events, they are not contained by political borders and can also affect areas far from the ignition points due to the atmospheric transport of the pollutant plumes.

A number of studies (e.g. Augusto et al, 2020; Im et al., 2018; Liang et al., 2018; Lin al., 2012, among others) report the influence of natural and anthropogenic emissions on air quality composition across different countries, especially PM and O_3. For wildfires, it is also important to take into account some factors which influence the plume dispersion, such as the duration and space evolution of the fire event and the meteorological conditions associated (Lazaridis et al., 2008).

An increase of cardiovascular and respiratory morbidity and mortality are some of the impact these contaminants can have on humans (Johnston et al., 2012; Tarín-Carrasco et al., 2019). For instance, there is a strong evidence of the relationship between PM in general and mortality, especially from cardiovascular diseases, for both long-term and short-term exposure (Anderson et al., 2012). Although some studies corroborate the existence of a link between the exposure to wildfire-related air pollutants and hospital admissions, visits to emergency clinics or even respiratory morbidity (Liu et al., 2015; Reid et al., 2016), the impacts on human health are difficult to quantify and the real effects still poorly known.

Regarding PM, a recent study focusing on 10 southern European cities revealed that cardiovascular and respiratory mortality associated to PM10 (particles with aerodynamic diameter below 10 µm) was higher on days affected by wildfires' smoke than in smoke-free days (Faustini et al., 2015). The authors also found that PM10 from forest fires increased mortality more than PM10 from other sources. So, the estimation of mortality due to exposure to wildfire-generated pollutants is key to manage health resources and the necessary public funds towards prevention and remediation, setting up appropriate policies and protocols (Rappold et al., 2012).

The two main factors to take into account for the wildfire's effects are the location and, most importantly, the size of the fire event (characterised by the respective burnt area). When the wildfire occurs close to a large conurbation, the population exposed is higher. But as Analitis et al. (2012) showed in their study, small fires do not seem to have an effect on mortality, whereas medium and large episodes (with burnt areas >1000 ha) have a significant impact on human health, which increases with the size of the fire.

Aiming to enhance the knowledge on the effects of wildfires on human health, this study describes the pattern of wildfires in Portugal for 16 years (2001-2016) and assesses the impact of those events on the country's population mortality during the fire season (June, July, August and September). In this work, the focus is placed on indirect effects of pollutants emitted by wildfires, namely assessing the influence of wildfire-generated PM10 on the Portuguese population mortality. The relationship between the size of the wildfire (characterised by the respective burned area) and PM10 and this same pollutant and mortality has been studied. The Nomenclature of Territorial Units for Statistics (NUTS) level 3 (NUTS III) geographical division has been used to be able to compare the effects of the fires in different parts of the country. Finally, monthly deaths due to all-cause (excluding injuries, poisoning and external causes) and cause-specific mortality (cardiovascular and respiratory) for all ages for each NUTS III has been studied. These causes have been selected due to their well-known connection with air pollution.

5.2 Methodology

In this study, the effects of short-term pollutants exposure due to wildfires on human mortality are quantified. The forest fire pollutant emissions were estimated for the period 2001-2016 during the summer months (June-July-August-September) in Portugal mainland (23 NUTS III and more than 10 million people). For this quantification, two steps have been followed.

First, an assessment of the incidence, patterns and variations of burned area on a large time frame and spatially integrated by NUTS III was done on the levels of air pollutants. PM10 and Burned area has been correlated through linear regression, while the mortality data and PM10 was correlated with Poisson regression. Data was processed and ordered by NUTS and by month and year. Finally, the correlation between the pollutants emitted by forest fires, the wildfires burned area and the different causes of mortality during the period 2001-2016 for the summer months was studied. The study is focused in PM since it is one of the main pollutants emitted by wildfires, which can increase PM concentrations up to 50% and more (Lazaridis et al., 2008). Moreover, there is a clear relation with several effects on human health (including mortality), in particular with respiratory and circulatory diseases (Reid et al., 2016, Kollanus et al., 2016, Liang et al., 2018). There was not enough PM2.5 data collected from the Portuguese air quality management network to establish a correlation (only 20 stations measure PM2.5 in the mainland). For all these reasons, this study is focused on PM10.

5.2.1 Target area

With 89 015 km² (9.11 Mha) mainland Portugal accounts for over 96% of the country's area and hosts over 10 million inhabitants in the west Iberian Peninsula (southwest Europe). With the largest urban areas along the west Atlantic coast, particularly around the capital Lisbon more to the south and the second largest city (Porto) in the north (see *Figure 5.1, left*), the country has most of its mountain ranges in the north, reaching 1993 m in Serra da Estrela. Although showing a Mediterranean climate, this topographic display leads to various climate patterns along the country, with increasing temperature and decreasing rainfall from northwest to southeast (Moreira et al., 2011; Oliveira et al., 2017). In terms of land cover, *Figure 5.1* (left) shows a predominance of agriculture by 2015 (over 50% and mainly in the south), followed by forests and shrublands, which comprise 43% of the territory (mainly in the north and southwest). This allied with high temperatures in the summer months represent a potential fire hazard, which unfortunately has been often verified almost every summer for many years.

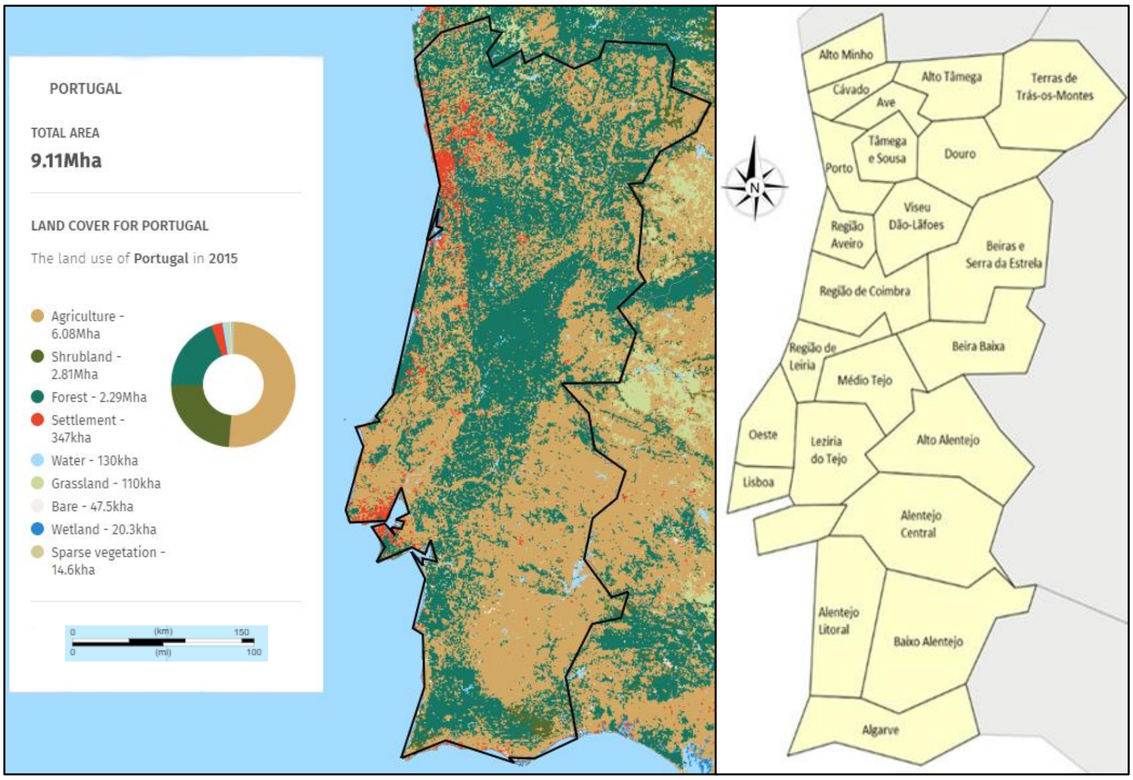

Figure 5.1: *(Left) Land cover in mainland Portugal in 2015 (GWF, 2020); (Right) Mainland Portugal NUTS III regions as included in this contribution.*

5.2.2 Datasets

5.2.2.1 NUTS III boundary data

The target domain was divided by NUTS (Nomenclature of Territorial Units for Statistics) level 3 (*Figure 5.1, right*) for Portugal mainland. NUTS is a geocode standard for referencing the subdivisions of countries for statistical purposes developed by the European Union, and are divided in three levels, established by each EU member country. The boundaries of the NUTS III files from mainland Portugal (in total, 23) were retrieved from the Eurostat web page (https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/administrative-units-statistical-units/nuts) with QGIS3 software. The downloaded data are for the 14 March 2019 version at a 1:60 million scale.

5.2.2.2 Wildfires data

The wildfire data, collected in the period from 2001 and 2016, was obtained from the Portuguese Institute for Nature Conservation and Forests (ICNF, 2019). For this study, forest fires occurring in the months of June, July, August and September 2001-2016 (the months with highest temperatures and drier conditions when more than 65% of fires happened) with more than 1000 ha of total burned area were selected and considered “large fires”. In total, there were 331 events under that category. This data was divided by month and year and the respective monthly and yearly sums were considered for each NUTS III level region. Ave, Alto Tâmega, Tâmega e Sousa, Oeste, Médio Tejo and Alentejo Litoral are the NUTS III where large fires during the study period were not found.

5.2.2.3 Pollutants data

The information available on the levels of pollutants was obtained from the Portuguese Environment Agency air quality network (https://qualar.apambiente.pt/qualar/index.php), established to monitor the concentrations of pollutants according to the European Legislation requirements (European Directive 2008/50/EC of 21 May 2008). The network is irregularly scattered throughout the country, with a stronger presence in the most populated areas. The isolation of pollutant emissions due to burnt biomass is quite complicated as it depends on parameters, such as vegetation type, the weather conditions on the burnt moment or the contribution of other sources, among others. For this reason, in this study, background stations (specifically urban, suburban and rural background) were selected, so that the direct impact of other urban and industrial sources such as road traffic, building heating and manufacturing combustions was avoided. Considering all the pollutants measured on the background stations, PM was the one with a potentially higher link to forest fires. And although some stations also measured PM2.5, the coverage was insufficient to draw any significant correlations, so PM10 was chosen in the end.

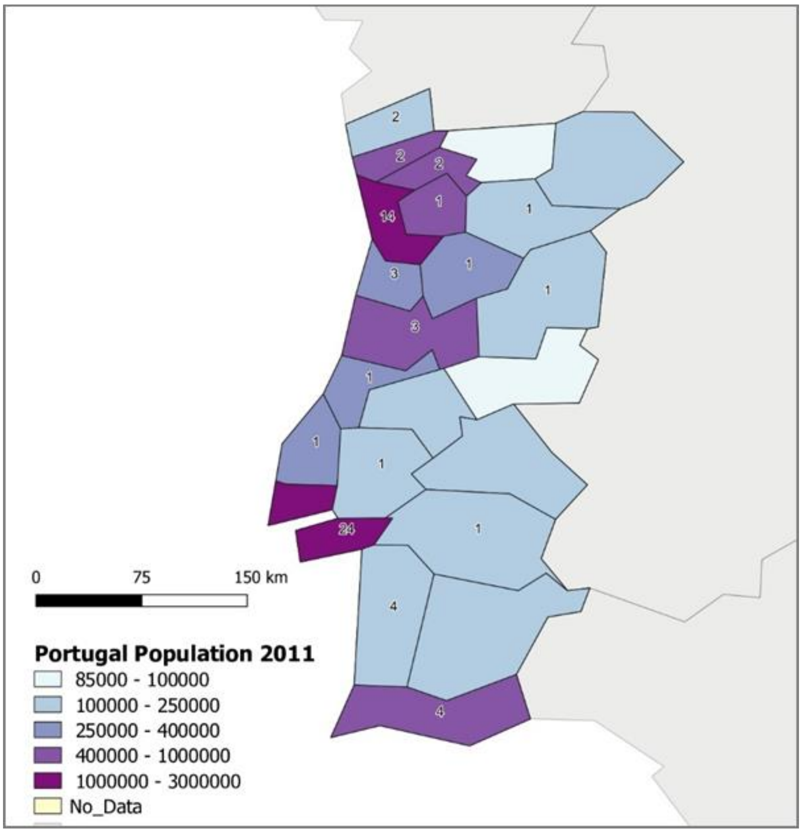

Figure 5.2: *Population of each NUTS III according to the 2011 Census (Statistics Portugal, 2019) and respective number of monitoring stations for PM10.*

As for the wildfires data, also here the time range was from 2001 to 2016 and only the months of June to September were considered, with monthly means used for the correlations. Concentrations of PM10 were obtained for mainland Portugal in all types of background stations (a total of 91 which cover 17 NUTS III, as shown in *Figure 5.2*) Given the uneven coverage of the target domain, most stations are located in the metropolitan areas of Oporto (14 stations) and Lisbon (24 stations) and in the rest of the coastal areas, where the higher population (NUTS III commonly above 250,000 inhabitants*, Figure 5.2*) demands a tighter control of the air quality, but where, in turn, not a lot of large wildfires occur due to the urbanized land use.

5.2.2.4 Mortality data

Mortality data covering the period from 2001 to 2016 was obtained from Statistics Portugal (INE, 2018). Monthly death counts due to all-cause (International Classification of Diseases (ICD-10), codes A00-R99) excluding injuries, poisoning and external causes; and cause-specific mortality: cardiovascular (codes I00-I99) and respiratory (J00-J99) were collected for each NUTS III region of Portugal, comprising all-age residents. These mortality causes were selected since they have been reported previously in literature as important in their connection with air pollution (Hoek et al., 2013; Liu et al., 2015; Kollanus et al., 2016; Münzel et al., 2018), in particular with particulate matter (PM). Other relevant mortality causes, such as Chronic Obstructive Pulmonary Disease (COPD, codes J40-J45) and asthma (ICD-10, code J47), were also considered, however the reduced number of deaths due to these diseases in the study period prevented the establishment of correlations.

5.2.3 Statistical analysis

5.2.3.1 Correlations between PM10 and burned area

Correlations between PM10 and the total burned area per month by NUTS III were estimated using Pearson correlations coefficients (Pearson, 1895). Pearson correlation is used to correlate two continuous variables having a normal distribution, while Poisson coefficients are used to correlate a count variable with a continuous variable. These methodologies are widely used in studies covering the topic of health impacts of air pollution (e.g. Islam and Chowdhury, 2017; Pallarés et al., 2019; Rahman et al., 2019; Rovira et al., 2020; among many others). Results were considered statistically significant if the p-value was $p<0.05$. Correlations were performed using the detrended data series of burned area and PM10 in order to remove the strong seasonal cycle of these variables and avoid spurious correlations. The detrending method follows Tarín-Carrasco et al. (2019), using the first-time difference time series.

5.2.3.2 Associations between burnt area, PM10 and mortality

The associations of monthly average PM10 levels, and the size of the wildfires (burnt area >1000 ha and burnt area <1000 ha) with mean monthly mortalities (all-cause, respiratory and cardiovascular causes) were studied for the months June, July, August and September for the period between 2001 and 2016. The effect estimates were obtained for each NUTS III region using Pearson regression models. The results were expressed as the Relative Risk (RR) of all-cause, cardiovascular and respiratory mortalities with a 95% confidence interval (95% CI). All regression models were performed using IBM SPSS Statistics 25.0 software.

5.3 Results and discussion

The results obtained in the study are presented as follows. First, the description of the situation in Portugal in terms of geographical distribution of the burned area is presented. Then, a summary of the PM10 concentrations during the summer months of the years 2001-2016 is presented. Finally, the correlations between burned area and PM10 and the potential associations of wildfire-derived PM10 and all-cause mortality is presented in this section.

5.3.1 Spatio-temporal patterns of wildfires

5.3.1.1 Burned area

From 2001 to 2016 period more than 2 million ha of forest were burned in mainland Portugal. Around 48% due to large fires (>1000 ha). During this period, the wildfires occurred on different areas in Portugal, as shown in *Figure 5.3*.

The north, centre and inland of Portugal are the areas with the highest number of wildfires and the highest burned area, being Beiras e Serra da Estrela and Beira Baixa. Also Lezíria do Tejo (in Alentajo) and Algarve (in the south) (*Figure 5.3*) can be found among the most affected areas (in number of wildfires and burned area). As can be seen in *Figure 5.1*, the north and centre of Portugal is where the most extensive forests in the country (Nunes et al., 2019), particularly abundant in pine and eucalyptus trees, two species that have been associated with extreme wildfire events (Maia et al., 2014).

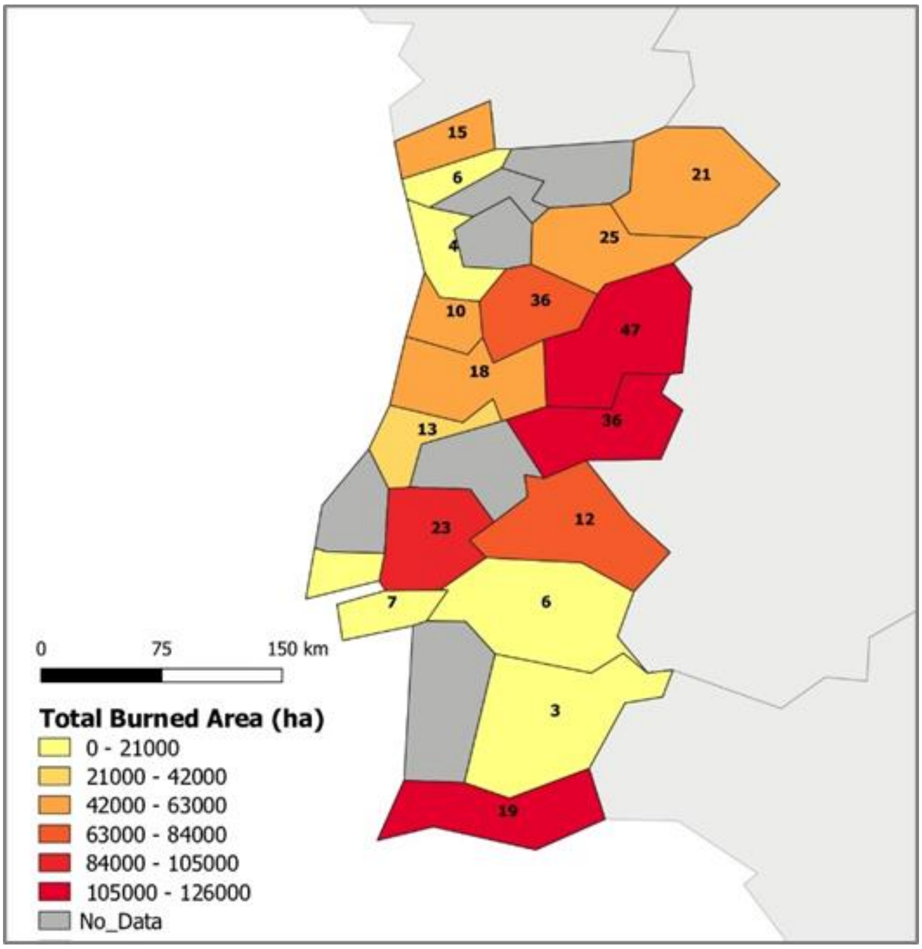

Figure 5.3: *Burned area and number of fires (>1000 ha) per NUTS III from June to September in the period 2001-2016.*

Additionally, dense Mediterranean forests over hard-to-reach mountains can also be found in these areas, which combined enhance the difficulty of the firefighting efforts. The Algarve, which despite being located in the south coast, also has some mountains with forests, surrounded by a considerably dry and arid terrain, especially in the summer (Nunes et al., 2019). Beira Baixa is the region which presented the most burned area during the period 2001-2016, with almost 124000 ha in total. But Beira e Serra da Estrela is the area where the highest number of wildfires was found, 47 in total. On the other hand, Lezíria do Tejo is the NUTS III region most affected by wildfires, considering the number of large fires and burned area together. Oeste and Area Metropolitana de Lisboa are the areas with a smaller number of large fires, only one during the target timeframe (since these are mainly non-forested areas). *Table 5.1* presents an overview of the burned area and occurrences of "large fires" by NUTS III areas in mainland Portugal.

Table 5.1: *Total burned area and occurrences of "large fires" by NUTS III areas in mainland Portugal in the period 2001-2016 in the months of June, July, August and September.*

	NUTS	**Study Months (N)**	**Months with Large Fires (N)**	**Number of Large Fires (N)**	**Total B.A. (ha)**
Norte	Alto Minho	64	7	14	53918
	Cávado	64	3	4	7731
	Ave	64	4	4	5410
	Alto Tâmega	64	10	21	48415
	Terras de Trás-os-Montes	64	7	10	28050
	A. M. Porto	64	5	8	40840
	Tâmega e Sousa	64	4	4	5706
	Douro	64	14	27	48907
Centro	Aveiro	64	3	6	17481
	Viseu Dão-Lafões	64	11	31	60744
	Coimbra	64	8	16	45673
	Beiras e Serra da Estrela	64	17	49	115503
	Leira	64	6	13	28347
	Médio Tejo	64	11	31	96947
	Beira Baixa	64	7	14	59032
	Oeste	64	1	1	1700
A. M. Lisboa		64	1	1	2756
Alentejo	Lezíria do Tejo	64	2	3	24404
	Alto Alentejo	64	4	12	70657
	Alentejo Central	64	3	6	1970
	Alentejo Litoral	64	3	5	16176
	Baixo Alentejo	64	2	2	9240
Algarve		64	9	19	107273

On the other hand, *Table 5.2* shows the yearly variability during the studied period of the number of the occurrences and burned area. In 2008 no wildfires over 1,000 ha of burned area occurred, whereas 2003 accounted for 81 of occurrences of large fires, which were responsible for 80% of the total burned area in that year. The data in *Table 5.2* suggests that it is not possible to perceive a yearly pattern of wildfires in Portugal regarding the occurrences, burned area or the contribution of large fires to the burned area, but other studies have shown a relationship with high temperatures and drought periods (Turco et al., 2019).

Table 5.2: *Number of wildfires and burned area (BA) by year for the period 2001-2016. From left to right: number of occurrences when the burned area is larger than 1000 ha; sum of burned area for fires lager than 1000 ha; percentage of burned area caused by large fires; and index between burned area and the number of occurrences.*

Year	Occurrences with BA>1000 ha	B.A >1000 ha	Total BA (ha)	%BA>1000 ha	BA/Occurrences (ha/#)
2016	22	85166	160458	53	3871
2015	8	16886	64978	26	2111
2014	3	6451	21114	31	2150
2013	26	71391	156688	46	2746
2012	11	48035	116204	41	4367
2011	6	9102	74686	12	1517
2010	25	60738	138797	44	2430
2009	9	21467	90541	24	2385
2008	0	0	17393	0	-
2007	2	6203	34036	18	3102
2006	7	21197	79536	27	3028
2005	61	172723	344554	50	2832
2004	32	75168	148194	51	2349
2003	81	375783	470617	80	4639
2002	17	30786	129731	24	1811
2001	21	34856	116706	30	1660

According to the 2016 EFFIS report, the south of Europe (Portugal, Spain, France, Italy and Greece) is the area most affected by wildfires since 1980 until today. In the last decades, Portugal was by far the country with the largest burned area, almost 50% between the southern European countries (Parente et al., 2018). But not only the south of Europe looks to be affected by wildfires, as areas in north of Europe which never had relevant wildfires are now suffering from these extreme episodes, as was the case of Sweden in the summer of 2018 (Lidskog et al., 2019).

5.3.1.2 Particulate Matter (PM10)

Regarding particulate matter, air quality monitoring stations are unequal spatial distributed. As mentioned previously, most of them are located near the coast, particularly in the in metropolitan areas of Lisbon and Oporto, the two most densely populated in the country; and only a few monitoring stations can be found inland. The mean highest concentrations of PM10 during the period 2001-2016 (June to September only) were observed in Oporto, with 31 µg m^{-3}; followed by Lisbon, Alentejo Central and Ave, with levels ranging from 26 to 29 µg m^{-3} (see *Figure 5.4*) Conversely, the NUTS III which present the lowest mean values, between 14-17 µg m^{-3}, are Oeste, Alto-Minho and Viseu Dão-Lafões. Despite these values, no NUTS in Portugal exceed the threshold value of PM10 (40 µg m^{-3} per year) established by the European Directive 2008/50/EC.

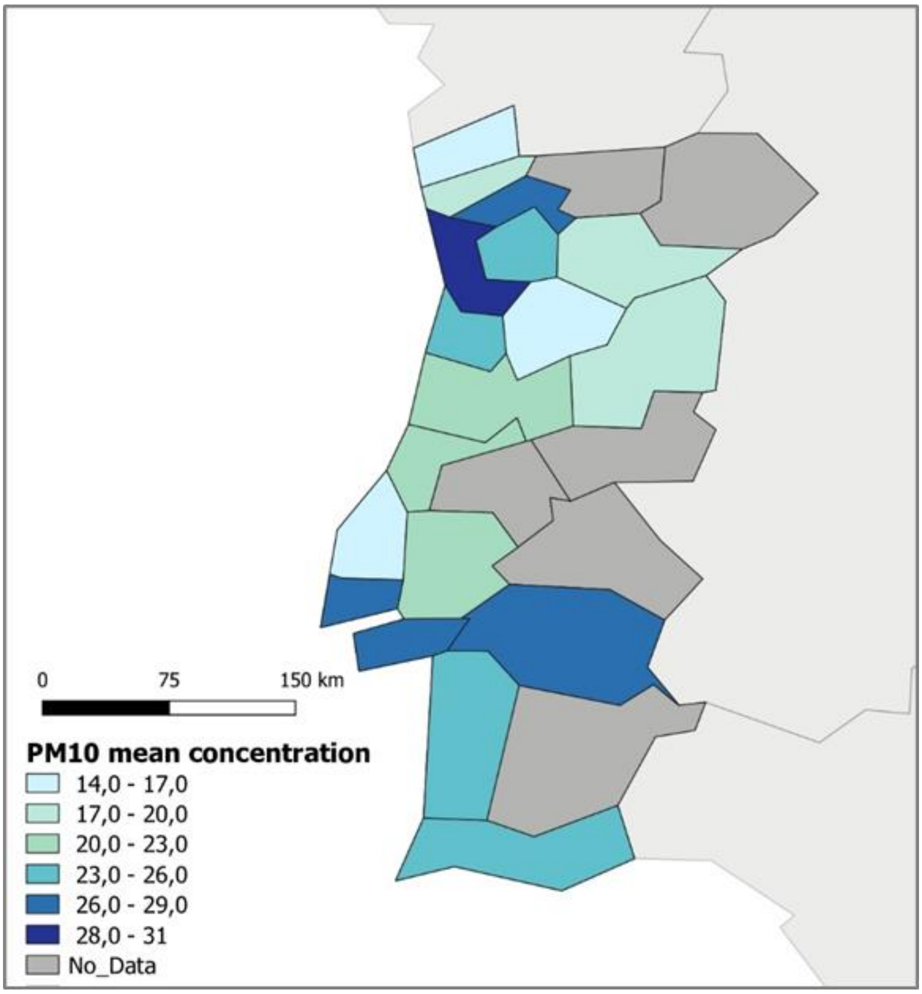

Figure 5.4: *Mean concentration of PM10 per NUTS III from June to September in the period 2001-2016.*

5.3.2 Relationship between burned area and particulate matter

Regarding correlation between burned area and PM10, a significant positive correlation was found for most of the studied NUTS III, represented by black dots in the map of *Figure 5.5*. The correlation is weaker for Alto Minho, Cávado and Algarve but the rest of studied NUTS present a strong correlation between both variables, peaking in Lisbon and Leiria with more than 0.98 at a confidence level of 0.95. Obviously, the location of the air monitoring stations may play a role in these correlations, especially when they are scarcer, but for these NUTS this is a good indication where the influence of wildfires on the emissions of PM10 is likely to be stronger. In fact, some authors have reported a contribution of wood burning to the PM10 load even in urban environments, where the presence of other PM sources tends to be higher (Fuller et al., 2014; Perrino et al., 2019).

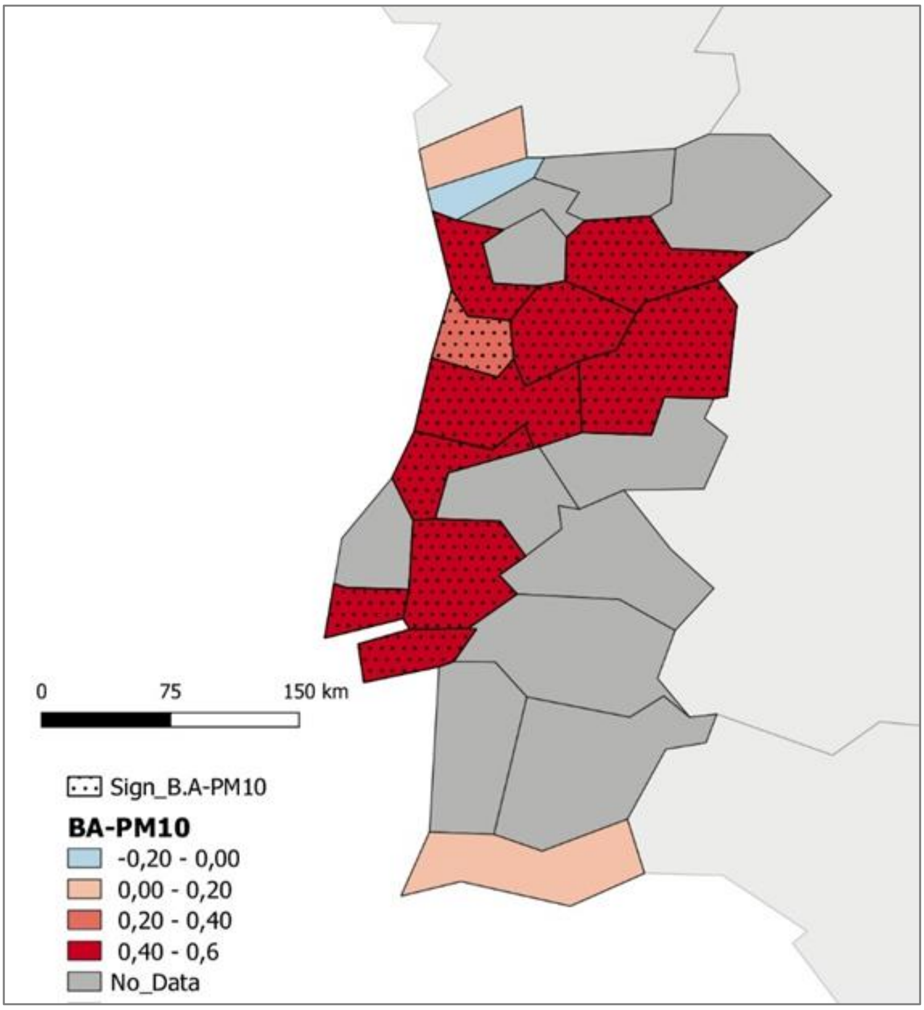

Figure 5.5: *Significance of Pearson correlations between burned area and PM10 for each NUTS III in the period 2001-2016 (from June to September; dots represent significant correlations).*

5.3.3 Impact of wildfires on all-cause mortality

The mortality counts for the period 2001-2016 (for the months June to September) in mainland Portugal are presented in *Table 5.3*, for each NUTS III region and all-cause, cardiovascular and respiratory-related deaths. Results show that almost 30% of all-cause and cardiovascular mortality occur during the extended summer (June, July, August and September), as do 26% of the respiratory mortality.

Considering that this period corresponds to one third of the year, the mortality in these months is slightly below what would be a regularly distributed percentage for a 12-month timeframe (33%). This is in line with the evidence that cold temperatures are in general more responsible for all cause deaths then warm ones (Lee et al., 2018; Scovronick et al., 2018).

Table 5.3: *Mean number of deaths that occurred on months affected by large fires in 23 NUTS III sub-regions of Portugal Mainland study area in 2001-2016.*

		Natural Deaths (N)		**Cardiovasc. deaths (N)**		**Respiratory deaths (N)**		
	NUTS	**All Months**	**Months with Large Fires**	**All Months**	**Months with Large Fires**	**All Months**	**Months with Large Fires**	**Inhabitants (2016)**
Norte	Alto Minho	44434	13213	16586	4731	4975	1293	233813
	Cávado	44307	12832	14136	3931	5964	1471	404664
	Ave	49068	14153	15736	4421	5754	1363	415664
	Alto Tâmega	20527	5324	6687	1864	2298	576	87941
	Terras de Trás-os-Montes	24664	7190	8083	2312	2623	633	109409
	A. M. Porto	221105	64366	67239	18660	24914	6252	1719021
	Tâmega e Sousa	50971	14623	18038	4847	6504	1574	420854
	Douro	39670	11648	13162	3642	4511	1143	193202
Centro	Aveiro	53380	15440	17705	4945	6664	1647	363752
	Viseu Dão-Lafões	48379	14170	17700	4918	6474	1679	256928
	Coimbra	81397	23648	28146	7718	10898	2807	439507
	Beiras e Serra da Estrela	53414	15699	17816	5036	6108	1558	218961
	Leira	45190	13259	14294	4015	5507	1426	287770
	Médio Tejo	49769	13908	16666	4595	5417	1444	236256
	Beira Baixa	22545	6624	8063	2306	2267	562	82731
	Oeste	60896	17819	22467	6285	6539	1660	358029
A. M. Lisboa		399704	118206	147172	41599	38931	10117	2821349
Alentejo	Lezíria do Tejo	45762	13505	16241	4491	5025	1397	239977
	Alto Alentejo	29145	8622	10391	2957	3690	923	108588
	Alentejo Central	33134	9602	12171	3252	2979	765	156207
	Alentejo Litoral	19241	5681	6916	1972	2294	635	94291
	Baixo Alentejo	30823	8988	11955	3317	3190	875	119024
Algarve		71445	21715	22591	6482	7926	2307	441469

Algarve, Alto Minho, Alto Alentejo and Lisbon are the NUTS with the higher percentage of all-cause mortality for the studied months, but the NUTS with more per capita incidence are Beira Baixa, Alto Alentejo, Baixo Alentejo and Beiras e Serra da Estrela, areas with lower population density and with mean higher age than the rest of the country.

Regarding cardiovascular mortality, the NUTS which present a high incidence are Algarve, Terras de Trás-os-Montes and Beira Baixa, with the latter, Baixo Alentejo and Alto Alentejo having a higher percentage of population affected.

Finally, the results obtained for respiratory mortality show that Algarve, Lezíria do Tejo and Alentejo Litoral are the NUTS which top the ranking in the summer months, whereas Alto Alentejo is the region with most population affected. Alentejo and Algarve suffer from high temperatures in the summer, which may also be an indicator that contribute for a higher mortality in general (Basu and Samet, 2002) but also due to cardiovascular and respiratory diseases (Pinheiro et al., 2014). As is the considerable afflux of tourists that increase their population in the same period, particularly in the Algarve. In Alentejo, the combination of high temperatures with an aged population and less health care resources available may be the justification to have the most population affected by mortality (Chen et al., 2019). In fact, this is a tendency that has been becoming stronger since the beginning of the XXI century, as the percentage of population over 65 years-old changed in Alentejo from 22,5% in 2001 to 25,4% in 2018, higher than the percentages in the whole of Portugal (from 16,4% in 2001 to 21,7% in 2018) (PORDATA, 2019).

The negative impact particulate matter can bring to human health is well established and can be translated into several types of diseases (Kim et al., 2015). Wildfires are an important source of this pollutant and the associations between wildfires and mortality were assessed in this work.

As shown in *Figure 5.6a*, four NUTS (Beiras e Serra da Estrela, Viseu Dão-Lafões, Coimbra and Lezíria do Tejo) present associations between wildfire-generated PM10 and all-cause mortality during the studied period, being these related to large fires in two of the NUTS, namely Lezíria do Tejo and Região de Coimbra. The wildfire origin of PM10 is corroborated by the positive significant correlations between PM10 and burnt area obtained for these four NUTS (*Figure 5.5*).

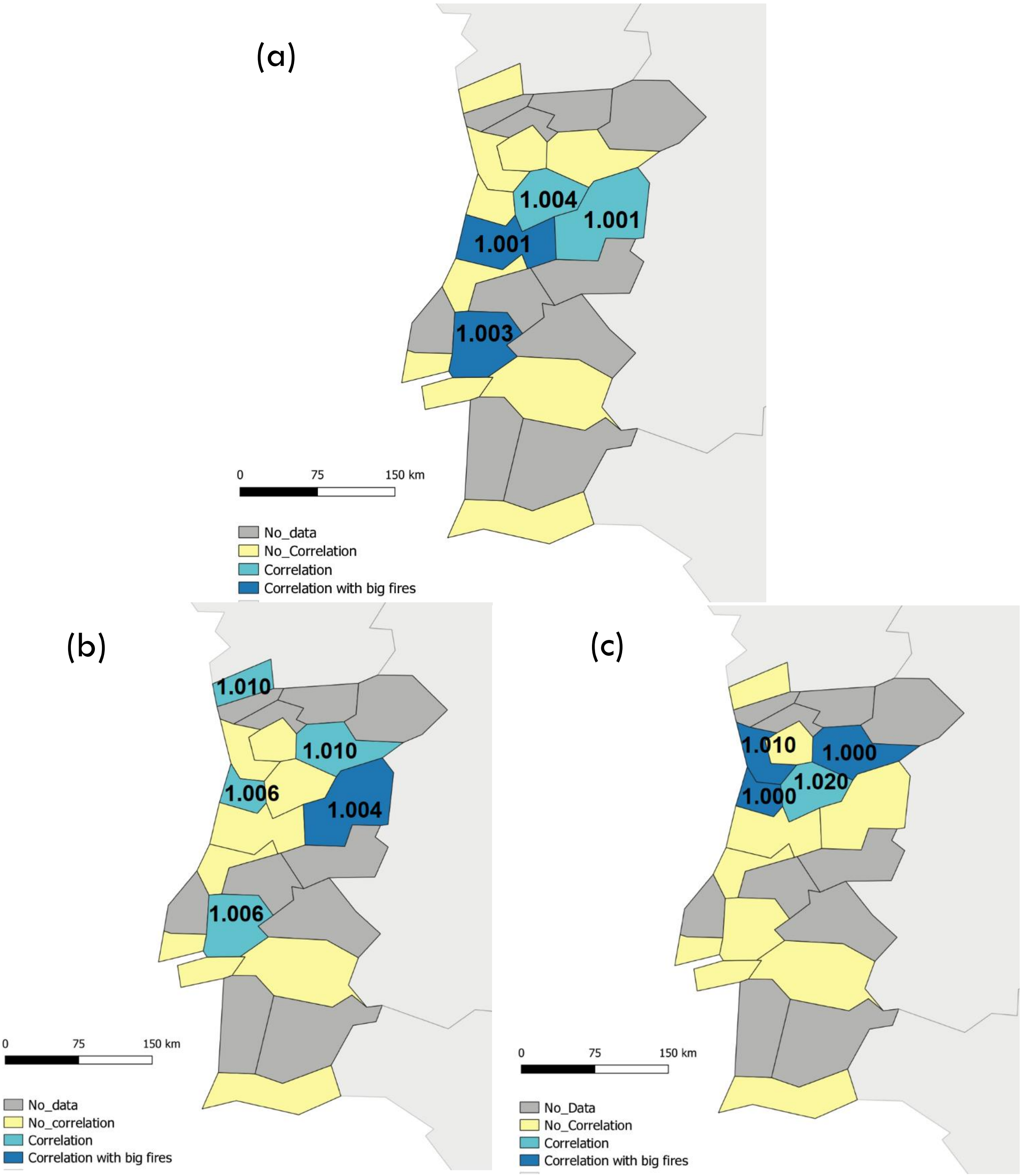

Figure 5.6: *Relative risks (RR, numbers) obtained from Poisson regression for PM10 and (a) all-cause mortality; (b) cardiovascular mortality and (c) respiratory mortality from June to September in the period 2001-2016 (light blue NUTS III regions indicate a significant result, p<0.05); dark blue represents significant result, p<0.05, with fires >1000 ha; yellow NUTS III regions present no significant results for the variables studied; grey NUTS III regions indicate that no data was available for correlations). Only significant RR are displayed.*

It is an evidence that particulate matter can enter the human body, arrive to the bloodstream and damage some organs or even provoke death due to cardiovascular afflictions like stroke or heart attack, among others, representing a clear hazard to public health (Brook et al., 2010; Hamanka and Mutlu, 2018). Regarding cardiovascular mortality, five NUTS present associations with PM10: Alto Minho, Douro, Região de Aveiro, Lezíria do Tejo and Beiras e Serra da Estrela, with only the last one being associated with the occurrence of large fires (*Figure 5.6b*). This NUTS region was the most affected by these events during the studied period, both in number (≈50) and respective burned area (>100 000 ha).

Beiras e Serra da Estrela counts with almost 50 large fires during 2001-2016, which involves high levels of PM10 in a short period of time, which might provoke damage in human health, particularly in an aged population (23,8 and 28,7% over 65 years-old in 2001 and 2018, respectively; PORDATA, 2019).

Particulate matter also can damage the human respiratory system. The risk depends on the size of the particle, which if very small can even reach the alveolus (Neuberger et al., 2004; Jo et al., 2017). For respiratory mortality, four NUTS present associations with PM10: Área Metropolitana do Porto, Douro, Região de Aveiro and Viseu Dão-Lafões, all located in the north of the country (*Figure 5.6c*). The majority had a correlation with the presence of large fires, except Viseu Dão-Lafões.

Aveiro and Oporto regions are urbanized areas with considerable industrial presence and a cooler and rainier climate year-round than in the south, and the chronic exposure to these conditions suggests that people may be more susceptible to have their respiratory tract affected by acute PM-releasing events like large fires.

In some NUTS III regions like Tâmega e Sousa and Área Metropolitana de Lisboa no correlations were expected since there was not a high number of large fires. In addition, these fires did not spread through a very large area. On the other hand, for Alentejo NUTS (Alto Alentejo, Alentejo Central, Alentejo Litoral and Baixo Alentejo), Oeste, Leiria, Beira Baixa, Médio Tejo, Cávado, Ave, Terras de Trás-os-Montes and Alto Tâmega pollutant data were missing or there was only one station for the whole region. Viseu Dão-Lafões is one of the NUTS with less PM10 concentration for the whole Portugal mainland. Finally, for Alto Minho and Algarve no correlation was found between wildfires and PM10.

5.4 Conclusions

Portugal is a country that suffers constantly from serious wildfire incidents, which are bound to pose a risk not only to chronically affected populations but also from acute impacts of the pollutants released in such events. In this work, analysing the summer months (June to September) on a lengthy timeframe (2001-2016), it was possible to find significant associations between burned area and mortality in some NUTS III regions of mainland Portugal (mainly inland and in the north), as well as a significant correlation between burned area and PM10.

In particular, large fires (in this study considered above 1000 ha of burned area) have an impact on the health of the population in some areas due to the emission of particulate matter. Moreover, in such severe events, the population exposed to a high concentration of pollutants in a short period of time should be considered as a risk modifier of the impacts of air pollution exposure (Desikan, 2017; Rappold et al., 2017).

During the studied period (2001-2016), the 48% of wildfires occurred in Portugal were large fires, more than 2 million ha of forest were burned in mainland Portugal. The areas that are more affected by number and size of wildfires are north, centre and inland of Portugal. Wildfires do not follow a pattern in number of the occurrences or size during the years studied. These evidences were found despite the difficulties that the uneven scattering of the air monitoring stations analysing PM10 in Portugal posed, since the areas where wildfires are usually more frequent (inland) are far from the urban centres (mainly along the coast), and thus, not abundant in air quality data availability due to the shortage (or even lack in some NUTS III) of monitoring stations. These regions also have an aged population, poorer economy and less health care resources, which can lead to an increase in the mortality rates in general. The socio-economic status of the population affected and the health care facilities and measures existing in the communities have to be taken into account (Oliveira et al., 2017), adding to the countless parameters that may affect these estimations which contribute to considerable gaps identified in this type of studies (Black et al., 2017).

During the summer months occur almost 30% of the deaths of all diseases and cardiovascular while for respiratory diseases mortality is around a 26%, so we can conclude that cold temperatures are in more responsible for all cause deaths than warm ones.

These episodes occurred during the summer months (June-July-August-September), when high temperatures and long episodes of drought increase the probabilities of undergo one of these extreme events. On a future ruled by climate changes, the high temperatures and long periods of drought that usually fuel big fires are expected to increase, thus leading the way for more extreme and intense events to occur, even outside the typically affected regions. Thus, more population will be exposed more frequently to high pollutant levels, affecting their general health, and increasing chronic diseases and mortality. Hence, restrictive policies and protocols to improve the effectiveness of preventive and mitigation actions must be enforced to face this environmental and societal issue.

Chapter 6

General conclusions and future perspectives

This PhD Dissertation presents an analysis of the impacts of air pollution-climate relationships with human health as the main objective. These impacts were covered in the different Chapters included in this document with different methodologies and perspectives. Each of these contributions (from Chapter 2 to Chapter 5) include their particular conclusions in detail, trying to shed some light to the individual objectives set in each Chapter.

Regarding the objectives proposed in Chapter 2, the impacts of regulatory pollutants in Europe on human health and their associated costs through linear exposure-response functions were studied, and the most important conclusions obtained were:

- The statistical epidemiological study conducted in Chapter 2 shows a clear relation between PM10 and its effects on human health (in this case, total deaths, TD; and deaths caused by respiratory diseases, DRD). This relation is stronger in central European countries.
- The modelling study depicted similar results as the epidemiological study. Large European conurbations (especially in eastern Europe) are the hotspots where the most important impacts of air pollution on several pathologies and diseases can be found. Also, high costs for the society have been found over Europe due to climate change action for present and future periods.
- The most important pathology studied in terms of cases and costs is premature deaths (PD). For this study, 418,700 cases and 158 billion € per year for the period 1996-2015 have been obtained, respectively. These numbers are expected to increase by 17% for both variables

(513,600 cases and 186 billion €) for the future period (2071-2100, RCP8.5 scenario).

- Under the climate change scenario, all of the studied pathologies are expected to increase due to climate penalty, especially in south-eastern Europe because of changes in projected in PM and O3. Conversely, northern Europe will benefit from climate change, reducing air pollution and therefore, its impacts on human health.

Chapters 3 and 4 focus on the premature mortality caused by fine particulate matter (PM2.5) for present (1991-2010) and future (2031-2050, RCP8.5 scenario) periods. For Chapter 4, a future mitigation scenario has been included, where the 80% of the produced energy comes from renewable sources. The premature deaths associated to changes on population dynamics over Europe have been studied as well. Non-linear exposure-response functions have been used to obtain the results on these aforementioned Chapters. The most important conclusions found are:

- Two different methodologies for assessing premature deaths have been included (GBD and GEMM methodologies). GEMM estimates 150,000 more premature deaths per year due to PM2.5 in Europe than GBD. The main differences are found over eastern and western European regions.

- The effect of climate penalty has been isolated. For the present period (1991-2010), the estimation of annual premature deaths due to PM2.5 over Europe using the GEMM methodology is 894,000. When the effect of climate change under the RCP8.5 scenario is isolated, the mortality could be increased by around 2,000 premature deaths (for a total of 896,000). Henceforth, the effect of climate penalty affects to western and eastern Europe, increasing the future mortality by +1.3 PD/100,000 habitants and +0.4 PD/100,000 habitants, respectively. Conversely, central Europe will benefit of the climate penalty, decreasing the annual premature mortality by -2.2 PD/100,000 habitants. This fact is caused by the reduction of PM2.5 levels over central Europe (that includes northern and central areas of the continent) under the RCP8.5 scenario due to the increased precipitation projected. Conversely, the climate penalty will have an important positive effect in the domain of western and southern Europe, where the concentrations of PM2.5 are projected to increase in the RCP8.5 scenario.

- The impact of changes of population dynamics was added to the previous estimation. Taking into account the effect of climate penalty and future population dynamics defined by the United Nations, the premature deaths increase by 71.96% for the period 2031-2050 (1,540,000 deaths), in spite of the decline in the European population. In contrast to the scenario in which population is invariable, premature deaths in central Europe in the future will increase. This fact is due to the population aging, because elderly people are more sensitive to air pollution.
- With respect to the implementation of the mitigation scenario previously described, the wide implementation of renewable energies could lead to a decrease of 60,000 annual premature deaths in the year 2050 (1,480,000 cases, a decrease of -4% comparing with the previous scenario). So, implementing renewable energy policies could reduce the number of premature deaths, being eastern Europe the most benefited area.
- The most important cause of premature deaths related to PM2.5 in all scenarios is caused by Ischemic Heart Disease (IHD) (over 50% of total premature mortality), with ~ 424,000 annual premature in the present and the climate penalty scenario. If considering the effect of population dynamics, the annual mortality for this endpoint increases to 736,000 cases. This number is nonetheless reduced on the mitigation scenario by renewables energy by -30,000 annual premature deaths. The second most important cause is CEV (Cerebrovascular Disease), with a ~ 10% contribution. LRI (Lower Respiratory Infection), LC (Lung Cancer) and COPD (Chronic Obstructive Pulmonary Disease) represent a 5%, 4% and 3%, respectively, of the total premature mortality. Other NCD (Non-Communicable Diseases) causes represent a 30% of the PD (Premature Deaths) in Europe.

It should be born in mind that these results are an estimation of the future mortality. The methodological approach used in Chapters 2, 3 and 4 can help providing an estimation of the impacts of air pollution on human health and its socio-economical consequences. These results are associated to different variables that sometimes are difficult to project, such as the death rate (which depends on each European country); the levels of air pollution (depending on the emission scenarios and the human influence on emissions like traffic, power generation or agriculture); and the demographic trends (elderly population, urbanization processes). The results presented show that the action of governments and public entities should focus on the regulation of air pollution and climate change; and implement mitigation policies leading to improving air quality and therefore, the wellness of the European citizens.

Finally, Chapter 5 covers the impacts of wildfires emissions. The relation between burned area, PM10 and mortality are correlated for Portugal. The target period covers from 2001 to 2016 for summer months (June, July, August and September). Large fires (> 1000 ha. burned area) are considered. The conclusions obtained are:

- Significant associations between burned area and mortality are found in some NUTS III regions of mainland Portugal (mainly inland and in the north), as well as a significant correlation between burned area and PM10. Large fires have an impact on the health of the population in some areas due to the emission of particulate matter.
- The 48% of wildfires occurred in Portugal during the studied period (summer months of 2001-2016) were large fires. In total, more than 2 million ha of forest were burned in mainland Portugal. The most affected areas by wildfires are north, central and inland of Portugal. Also, wildfires do not follow a pattern regarding the number of the occurrences or size during the years studied.
- During the summer months, almost 30% of the deaths related to all diseases and cardiovascular endpoints occur, while for respiratory diseases mortality is around 26%.
- In the future, climate change is expected to increase the frequency and extent of these episodes. High temperatures and long episodes of drought increase the probabilities of occurrence of one of these extreme events.

Therefore, more population will be affected for these events due to the exposition to higher pollutant levels, affecting their general health, and increasing chronic diseases and mortality. Hence, restrictive policies and protocols to improve the effectiveness of preventive and mitigation actions must be enforced to face this environmental and societal issue.

- Also, for this study some limitations can been found. In Portugal, air monitoring stations are located in the urban centres (mainly along the coast), while wildfires are usually more frequent inland. Also, the inland region has an aged population, poorer economy and less health care resources, which can lead to an increase in the mortality rates in general. Better coverage of station data could provide a more accurate estimate.

In summary, air pollution and climate change have serious impacts on human health provoking the increase of hospital admissions, chronic diseases or even premature deaths. In this sense, this Thesis helps understanding the relationship between air pollution and its impacts on human health and the indirect effects of climate change. Despite the inherent limitations of this type of studies, combining modelling of atmospheric chemistry/climate together with the statistical treatment represent a good tool to obtain and approach to the impacts of climate change and air pollution on the future European dwellers health. Further works can be focused on:

- Study of other future climate change scenarios. Thesis focuses on the RCP8.5 scenario as an upper limit of the feasible climate change. It could be interesting to analyse the differences between the different Representative Concentration Pathway scenarios proposed by the IPCC.

- Also, the study of other future mitigation scenarios could give an idea of the sources with a high contribution to air pollution and, hence, impacting human health. In this sense, source contribution scenarios where sources as traffic or cattle industry are reduced could be of a higher interest for future mitigation policies.

- This Thesis is focused mainly on cerebrovascular and respiratory endpoints and premature mortality; but recent studies show the relationship between air pollution and other illnesses as neurodegenerative diseases. Focusing on future studies relating air pollution and climate change to neurodegenerative diseases could be a good option to know the future impacts on human health. Also, further works should be devoted to understanding the effects of climate change on Communicable Diseases, which will increase their range of action affecting areas where, for a present climate, their impact is limited.

- Other pollutants have important effects on human health. This Thesis is focused mainly on PM, but other regulatory pollutants as tropospheric O3 are also related with important impacts on human health. As the concentration of this pollutants enhances with temperature (and especially during heatwaves), climate change could make the impacts of this pollutant even more dangerous for dwellers.
- The results obtained in this study clearly show that elderly people are very sensitive to air pollution. Estimating the effects of air pollution on other groups of sensitive population as pregnant women or neonate children could be interesting to prevent the impacts to population in future episodes of high concentrations of atmospheric pollutants.

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