Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 14 September 2022 doi:10.20944/preprints202209.0207.v1

Article

HEALTH IMPACT ASSESSMENT OF AIR POLLUTION UNDER A CLIMATE CHANGE SCENARIO: METHODOLOGY AND CASE STUDY APPLICATION

Sílvia Coelho [1], Joana Ferreira [1,*], David Carvalho [3] and Myriam Lopes [1]

[1] CESAM & Department of Environment and Planning, University of Aveiro, Portugal; silviacatarina@ua.pt; jferreira@ua.pt; myr@ua.pt
[2] CESAM & Department of Physics, University of Aveiro, Portugal; david.carvalho@ua.pt
* Correspondence: jferreira@ua.pt

Abstract: The World Health Organization estimates that every year air pollution kills seven million people worldwide. As it is expected that climate change will affect future air quality patterns, the full understanding of the links between air pollution and climate change, and how they affect human health, are challenges of future research. In this scope, a methodology to assess the air quality impacts on health was developed. The WRF-CAMx modelling framework was applied for the medium-term future climate (considering the SSP2-4.5 scenario) and for the recent past (considered as baseline). Following the WHO recommendations, mortality health indicators were used to estimate health impacts of long-term exposures. For that, the Aveiro Region, in Portugal, was considered as a case study. Future climate results indicate the occurrence of higher temperatures, and lower total precipitation. Despite that, improvements in the main pollutants' concentrations, and consequently in the reduction of the related premature deaths are foreseen, mainly due to the reduction of pollutants emissions imposed by the European legislation for the upcoming years. The applied approach constitutes an added value in this research field, being crucial to anticipate the effects of climate change on air quality and evaluate their impacts on human health.

Keywords: SSP (Shared Socio-economic Pathway) scenarios; air quality; WRF-CAMx; numerical modelling; urban areas; health impact assessment; premature deaths.

---

1. Introduction

Nowadays, air pollution and climate change are two of the biggest environmental and health threats, with increasing concern among people worldwide [1], and it is expected that this concern will continue for the next decades [2]. More than 70% of European Union (EU) population live in urban areas [3], particularly in high densely populated cities, where economic activities cause high levels of air pollution [4]. Citizens' exposure to air pollutants like particulate matter with a diameter of 10 microns or less (PM10) and with a diameter of 2.5 microns or less (PM2.5), nitrogen dioxide (NO_2) and ozone (O_3) has been threatening human health. The EU Air Quality Directive (Directive 2008/50/EC [5]) aims to protect health, vegetation and natural ecosystems, through the definition of limit and target values for those air pollutants, among others. In 2020, due to the lockdown measures introduced to minimise the spread of Covid-19, less than 1% of the EU urban population lived in zones with PM2.5 and NO_2 concentrations above the EU limit values, while 12% of citizens were exposed to O_3 and 11% to PM10 levels above EU standards [4]. However, when considering the new 2021 World Health Organization (WHO) air quality recommendations [6], in 2020, the EU urban population exposure raised to 96% for PM2.5, 89% for NO_2, 71% for PM10 and 93% for O_3 [4]. The EU Clean Air Programme [7] sets the long-term objective of complying with WHO air quality recommendations, based on what is considered necessary to ensure the protection of human health [4]. Following this, the European Green Deal [8] proposes a revision of the ambient air quality directives, aiming to align EU air quality standards more closely with WHO recommendations [4]. The WHO estimates that every year ambient air pollution kills around 4.2 million people worldwide due to stroke, heart disease, lung cancer, lower respiratory infections, and chronic obstructive pulmonary disease [9]. In 2019, only in the EU, the estimated premature deaths attributable to the long-term exposure to PM2.5, NO_2 and O_3 concentrations were around 307000, 40400 and 16800, respectively [10].

As air pollution is strongly dependent on meteorological conditions [11,12], it is consequently sensitive to climate change. According to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) [13], it is expected that climate change will have complex effects on chemistry, transport and deposition of local air pollutants. IPCC also refers to urban areas as the ones that must respond to climate change risks [13,14], mostly due to the complex interactions between social, economic, and environmental stressors [15–17]. Indeed, climate change impacts in urban areas has recently become an important and urgent research topic. [18]. The full understanding of the links between climate change and air pollution in urban areas, and how they affect human health, are nowadays research challenges. Also, future emission scenarios, in line with the European Green Deal and the EU Clean Air Programme, should be considered due to their higher impact on air quality patterns.

In the light of the above, the main aim of this work is to assess air pollution effects on human health at urban scale for the medium-term future, considering a climate change scenario, through the application of a numerical modelling system, having the Aveiro Region, in central Portugal, as a case study.

The Aveiro Region is located in the central part of Portugal, close to the Atlantic Ocean, with an area of 1 693 km^2 and around 370 000 inhabitants. The Aveiro Region includes eleven municipalities which are distinguished by their geography, economy, activity sectors and population density [17,19]. The major economic sector of the region is manufacturing industry, accounting for 50% of the region's income [20], followed by tourism and services [19]. The most industrialized municipalities are typically located along the coast, closer to one of the most important seaports in Portugal. Rural municipalities, where agriculture plays an important role, are mainly situated in the inland parts of the region [21]. According to the Köppen climate classification [22], Aveiro Region is classified as a warm-summer Mediterranean climate (Csb). Despite the climate and the open landscape characteristic of many of the municipalities in the Aveiro Region, which favor the pollutants dispersion, PM and NO_2 exceedances occur occasionally in some areas of the region [17,19].

This work, easily applicable to other case studies, will fulfill the need for further studies that assess the future climate effects on air quality, with a high-resolution level, to support the identification of early climate and air pollution adaptation strategies. Additionally, several scientific communities, policy makers and citizens, may benefit from the advances in the coordination between climate change, air quality and health impact assessments for urban areas.

The present work is organized as follows: Section 2 describes the climate and air quality modelling system, as well as the main results; the health impact assessment, with both WHO approaches and results, is presented in Section 3; conclusions are drawn in Section 4.

2. Climate and Air Quality Modelling

This section presents the methodology followed to assess the medium-term future climate and its impacts on air quality over Aveiro Region (section 3.1), and the analysis and discussion of the obtained results (section 3.2).

2.1. *Methodology*

To assess the future climate and air quality patterns on the study area, the WRF - Weather Research and Forecasting Model [23] together with the CAMx - Comprehensive Air Quality Model with Extensions [24] modelling framework was applied. These models have been widely used to assess air pollution in different case studies worldwide, and more specifically in Portugal, with reliable and realistic results [12,17,25].

Three nested domains with increasing resolution at a downscaling ratio of five were used, with the outermost domain of 30 km horizontal resolution centered over the Iberian Peninsula, and the innermost domain of 1.2 km horizontal resolution, with 75 × 75 horizontal grid cells, focusing on the Aveiro Region (Figure 1).

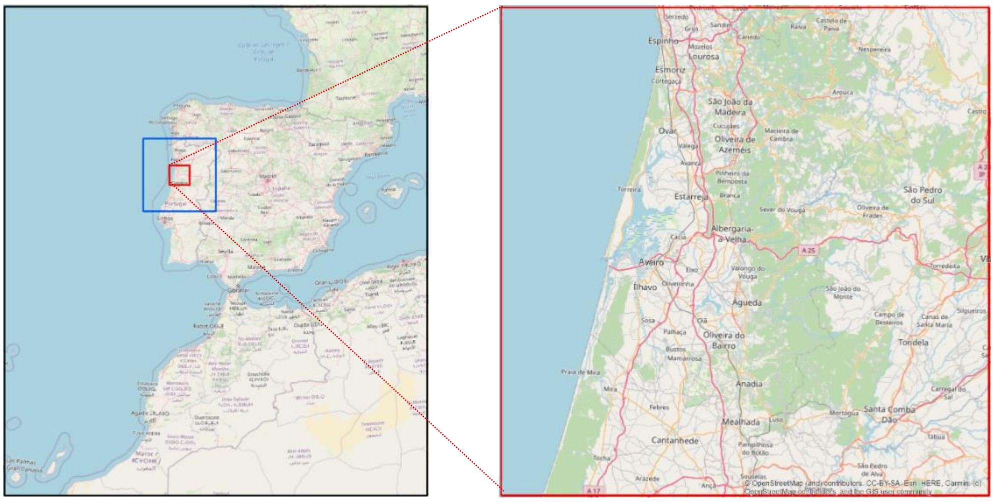


Figure 1. WRF-CAMx modelling system domains with 30 (D1 - within the black rectangle), 6 (D2 - within the blue square) and 1.2 (D3 - within red square) km resolution.

The WRF model was forced by the Max Planck Institute for Meteorology Earth System Model version 1.2 (MPI-ESM1.2-HR) [26], with 0.938° horizontal resolution and 95 vertical levels. Other works [27,28] show that MPI-ESM is considered as one of the best global models to predict the climate in Europe. The WRF physical configuration, selected based on previous studies [12,28–31], was as follows: microphysics - WRF Single-Moment 6-class scheme [32]; longwave and shortwave radiation - RRTMG [33]; surface layer - MM5 [34]; land surface - Noah [35]; planetary boundary layer - YSU [36]; cumulus - Grell-Freitas [37]; and sea surface temperature 6-hourly update. To keep the WRF downscaling consistent with the large-scale atmospheric dynamics of the forcing data, spectral nudging was used in the outermost domain for atmospheric waves larger than 1000 km in latitude and longitude.

The modelling system was applied for two years, one statistically representative of the recent past (2014), considered as a baseline, and the other statistically representative of the medium-term future climate (2055). Based on previous studies [12,31,38], the selection of the representative years was supported by a climatological analysis of every year of the periods 1995-2014 (for the recent past) and 2041-2070 (for the medium-term future) and compared with the average of each period, to find the year with the lowest climate anomaly. This analysis was performed for temperature and precipitation as they are considered by the scientific community as fundamental for describing the climate [13] and are particularly important in air pollutants transport and deposition [39–42]. For the medium-term future climate, the new SSP2-4.5 (Shared Socio-Economic Pathway) scenario [43] was applied. As stated by Riahi et al. [44], SSP2-4.5 is part of the "*middle of the road*" socio-economic pathway, considering medium challenges for both climate change adaptation and mitigation and a "*medium pollution control*" scenario, with a nominal 4.5W·m^{-2} radiative forcing level by 2100.

CAMx initial and boundary (every 6 hours) conditions for the outermost domain were provided by the Community Atmosphere Model with Chemistry (CAM-Chem [45]) global chemical model, with 0.9° x 1.25° spatial resolution. For the recent past climate, anthropogenic emissions were taken from the EMEP (European Monitoring and Evaluation Programme) emission inventory [46], and was spatially disaggregated according to the methodology described in Ferreira et al. [25] and speciated into the Carbon Bond 6

(CB6) chemical mechanism species considered in the CAMx simulation [47]. For the medium-term future climate, emissions were estimated by adapting the methodology defined by Sá et al. [48] and considering the emission projections from the Portuguese roadmap for carbon neutrality [49], in line with SSP2-4.5 scenario considered in WRF simulation. According to this methodology, medium-term future climate emissions, when compared to the recent past, show an average emission reduction of approximately 33% for PM10, 38% for PM2.5, 68% for NOx, 27% for NMVOC, 70% for CO, 15% for NH_3 and 35% for SOx. Note that these are average emission reductions for all source activities despite the emission projections foresee an increase for some activity sectors (e.g., NMVOV and PM10 in industrial combustion and processes sector, CO and NMVOC in agriculture).

2.2. *Results and Discussion*

For both climate and air quality assessment, results obtained for the medium-term future climate were compared with the results for the recent past. The comparison was made for the following periods: (i) annual; (ii) spring (March to May); (iii) summer (June to August); (iv) autumn (September to November); and (v) winter (December to February).

For the climate change assessment, mean temperature and total precipitation were analyzed. Figure 2 shows the annual average of mean temperature and total precipitation, for the medium-term future climate, recent past climate, and the difference between them. Seasonal results can be found in Appendix A, in Figure A1 and Figure A2.

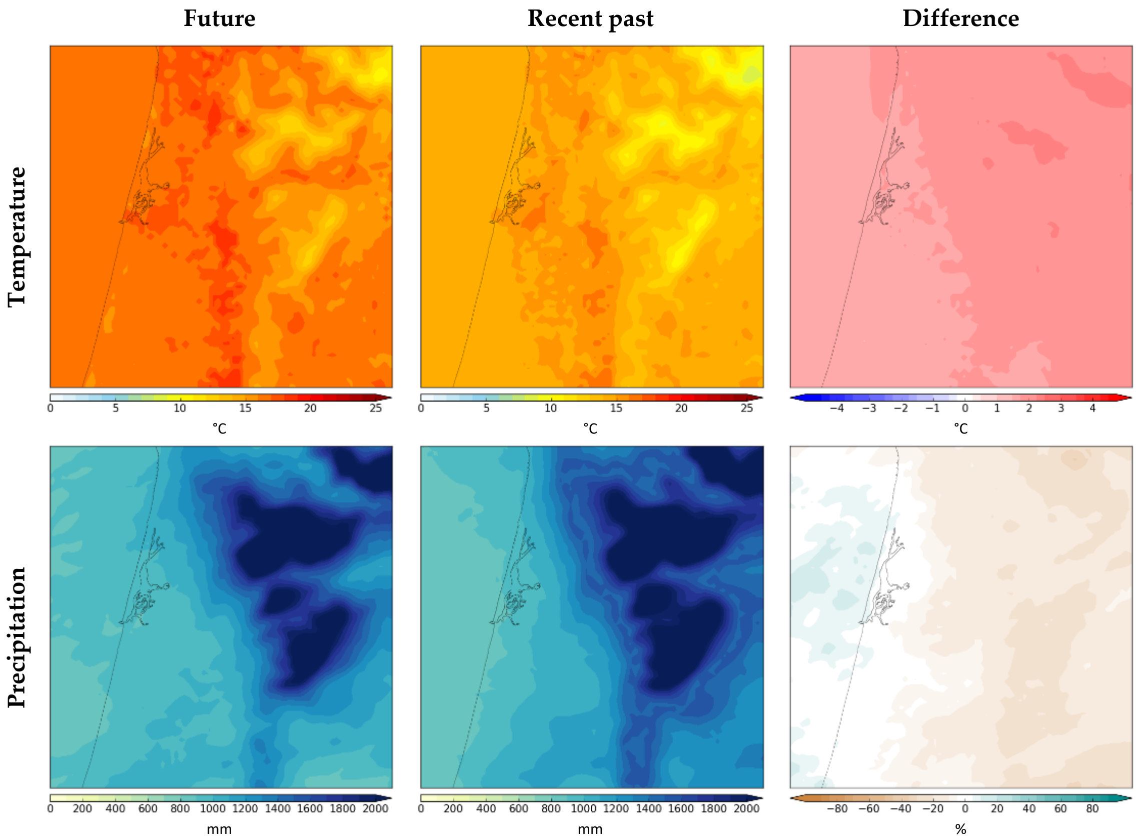
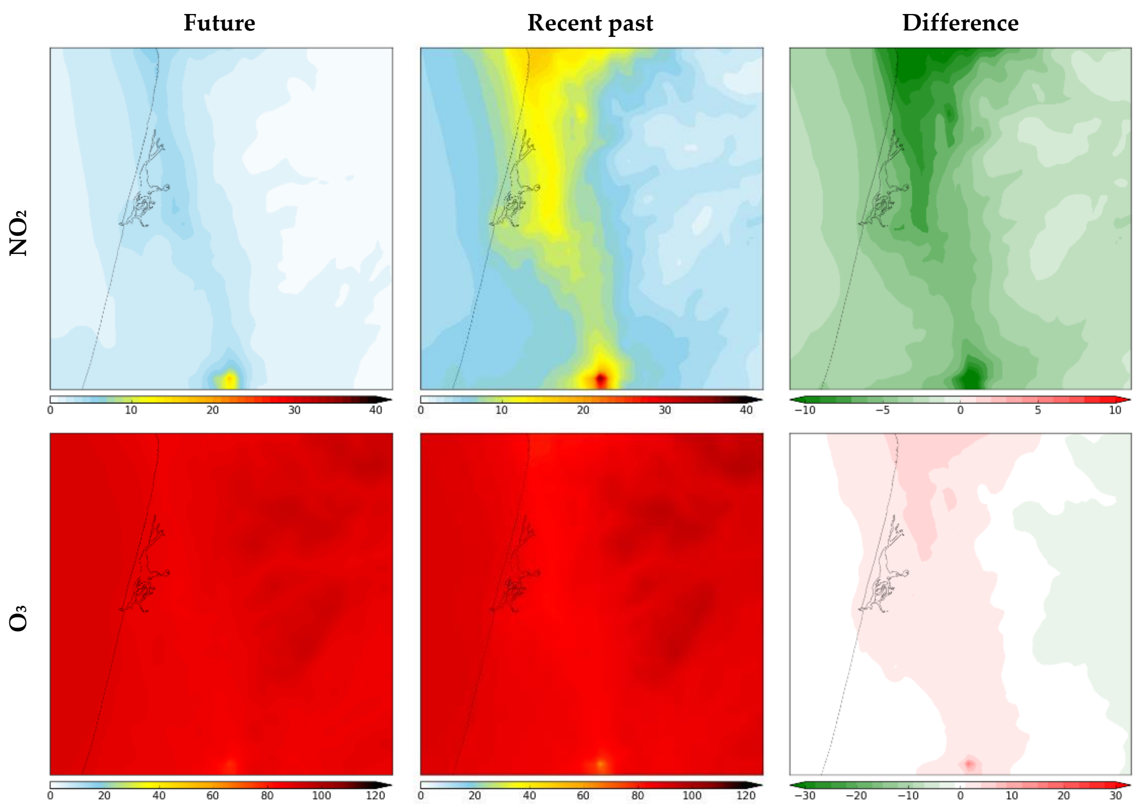


Figure 2. Annual mean temperature and total precipitation, for the medium-term future climate (2055), recent past climate (2014) and the difference between them (2055 – 2014).

The differences between the medium-term future climate and the recent past climate for the annual mean temperature, show an increase in future temperature between 1 and 2°C, with lower differences estimated closer to the coastline and in the lower altitude areas. For the annual total precipitation, a decrease up to 40% is expected in some areas of the region. Over the coastline no differences are projected in total precipitation and an increase, between 10 and 20%, is predicted over some parts of the Atlantic Ocean. Notwithstanding, in agreement with what has been shown in other studies [13], a trend towards reduced precipitation in the medium-term future is clear. This precipitation trend, together with the higher temperatures projected, will lead to drier conditions, as it has been already observed in southern Europe countries [50]. Regarding the seasonal analysis, results show different variations. Highest temperature differences are projected for the summer, where mean temperature can increase up to 4°C, and the lowest differences projected for autumn, with some parts of the study region for which differences are not expected. Moreover, for none of seasons, a temperature decrease is expected in the future. Differences in precipitation also exhibit several variations across the seasons. For summer and autumn, a precipitation reduction around 80% and 45%, respectively, is expected in almost the entire study region. However, in winter and spring, the precipitation decrease projected for the medium-term future is only foreseen for the inland regions of the domain, with an expected increase over the Atlantic Ocean and coastal areas.

These future climate patterns will have complex effects on chemical reactions, transport, dispersion and deposition of air pollutants [40]. Temperature affects the chemical reactions rates as well as the dispersion and deposition of chemical compounds [41,42]. The precipitation washout also plays an important role in removing pollutants from the atmosphere, by wet deposition [51,52]. Figure 3 shows the annual average concentration of NO_2, PM10 and PM2.5, and the annual average concentration of the maximum daily 8 h mean O_3, for the medium-term future climate, recent past climate, and the difference between them. Seasonal results can be found in Appendix A, in Figure A3, Figure A4, Figure A5 and Figure A6.



 doi:10.20944/preprints202209.0207.v1

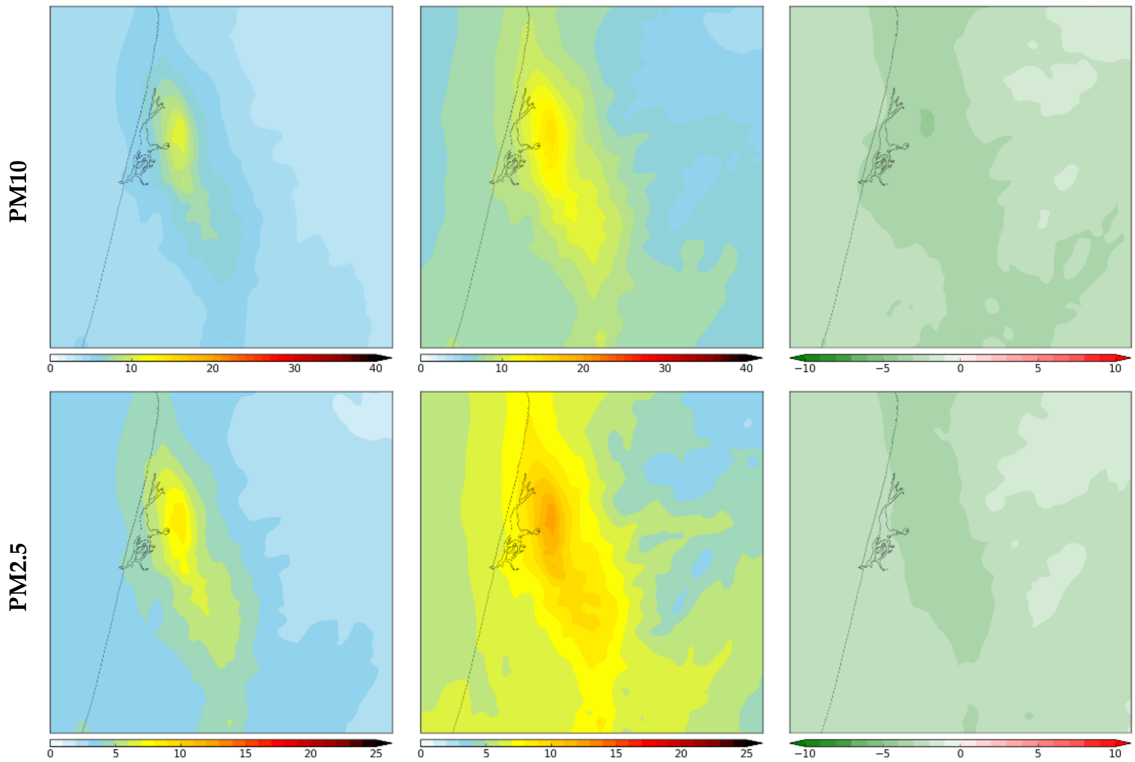


Figure 3. Annual average concentration of NO_2, PM10 and PM2.5, and the annual average concentration of the maximum daily 8 h mean O_3, in $\mu g.m^{-3}$, for the medium-term future climate (2055), recent past climate (2014) and the difference between them (2055 – 2014). For future and recent past maps, the maximum value of the color scale represents the EU limit value.

For both periods analyzed, medium-term future and recent past climate, all pollutants show similar spatial patterns, but with different magnitudes of the concentrations. The differences between the medium-term future climate and the recent past climate, result in a decrease in the annual average concentration of NO_2, PM10 and PM2.5 up to 10, 4 and 3 $\mu g \cdot m^{-3}$, respectively. For the medium-term future climate, the differences in the annual average concentration of the maximum daily 8 h mean O_3 show decreases (up to 4 $\mu g \cdot m^{-3}$) and increases (up to 10 $\mu g \cdot m^{-3}$), depending on the area. When analyzed seasonally, O_3 shows variations along the seasons, while the remaining pollutants maintain a similar behavior to the annual one. For NO_2, major differences are found in the same areas where higher concentration values are obtained for the recent past, namely: (i) in the North of the domain, where part of the Porto metropolitan area (the second largest urban area in Portugal) is located, and that influences Aveiro Region air quality due to the pollutants transport by the North/Northwest dominant winds; and (ii) in a small area in the South, the site of one of the major cement factories in Portugal. The 68% of NOx emission reduction projected for the future, mostly related with transportation and industry sectors, will lead to this reduction in the NO_2 concentrations. In contrast, in the locations with higher NO_2 concentration reductions, an air quality deterioration due to O_3 pollution will be expected, due to the reduction of NOx values, but also due to the projected temperature increase, favoring photochemical phenomena. Concerning PM10 and PM2.5 results, higher concentrations were estimated over the most industrialized areas of the Aveiro Region, where the major concentration reductions are also projected for the future. Although a decrease in total precipitation is expected in the Aveiro Region, which could lead to an increase in both PM10 and PM2.5 concentrations [51,52], this does not happen due to the reduction of the future PM emissions considered.

For the medium-term future, the projected decrease in NO_2, PM10 and PM2.5 annual concentrations will ensure that the limit values imposed by the European Union Air Quality Directive [5] will not be exceeded. For the same period, despite the projected increase in the maximum daily 8 h mean O_3 concentrations, they will also be below the defined

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 14 September 2022 doi:10.20944/preprints202209.0207.v1

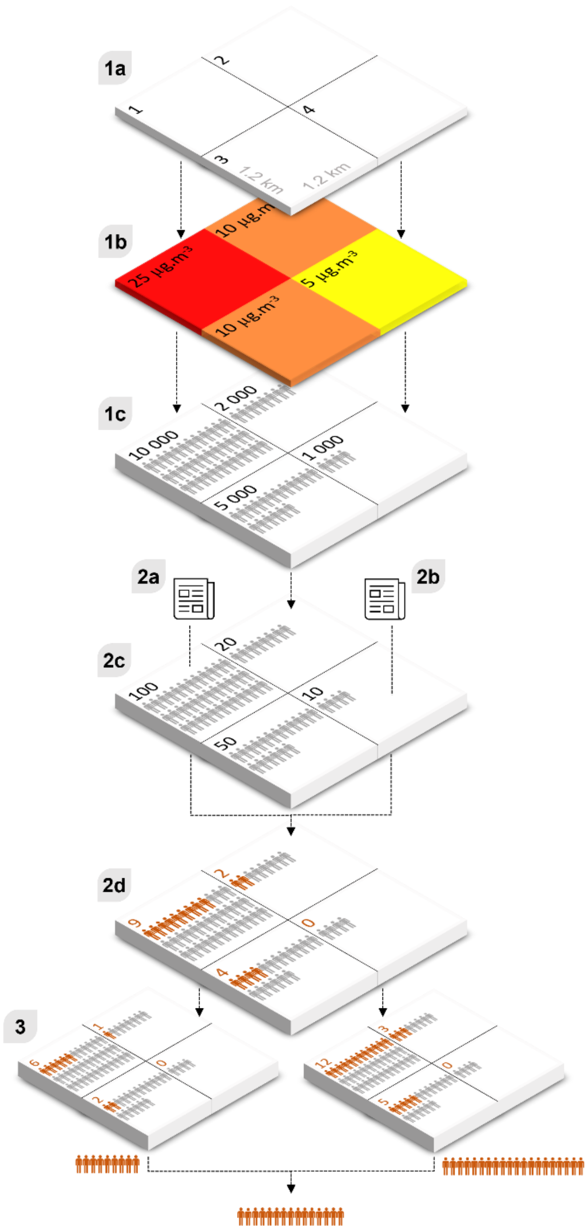
target values for protection of human health. However, if the new WHO air quality guidelines [6] are considered, future annual concentration of PM2.5 and maximum daily 8 h mean O_3 will be above the recommended air quality guideline levels (5 and 60 µg·m^{-3}, respectively), in some areas of the Aveiro Region.

3. Health Impacts Assessment

This section presents the methodology followed to perform the health impact assessment for medium-term future climate and recent past climate (section 4.1), and the analysis and discussion of the obtained results (section 4.2).

3.1. Methodology

Long-term health impacts of PM2.5, NO_2 and O_3 exposures were estimated, since they are the most harmful pollutants, with strongest health impacts evidence, according to WHO [53]. For the selected pollutants, following the approach usually applied in the EEA (European Environment Agency) annual health assessments, described in Soares et al. [54], mortality health outcomes were analyzed since it is the most serious health impact and the one with the most robust scientific evidence [55]. For O_3, mortality due to respiratory diseases was considered, while for PM2.5 and NO_2, all cause (natural) mortality were considered, both at ages above 30 years. The health outputs were traduced in the number of premature deaths, for the population affected by air pollution living within the study area. According to WHO [56], the health impact assessment can be performed in three major steps, namely: (i) population exposure assessment; (ii) health risk estimation; and (iii) uncertainty calculation. Figure 4 shows the health impact assessment scheme, with an example for PM2.5, long-term exposure, all cause (natural) mortality, using WHO 2013 methodology and hypothetical concentration and population values.



Population exposure assessment:

1a) Grid: the area for which the health risk assessment will be calculated consists in a 4 cells grid with 1.2x1.2 km² horizontal resolution.

1b) Concentration Map: the air quality modeling results, for cells 1 to 4, show PM2.5 annual concentrations that vary between 5 and 15 µg.m^{-3}, for the year under analysis.

1c) Population/Exposure: the population is distributed across the grid and the exposure is calculated. For example, in cell 1, 10000 inhabitants are exposed to 15 µg.m^{-3} of PM2.5.

Health risk estimation:

2a) Baseline Concentration: the baseline concentration for PM2.5 is 0 µg.m^{-3}, meaning that, for instance, for grid 1 the effect of the whole range of 15 µg.m^{-3} of PM2.5 will be estimated.

2b) Relative Risk: in case of PM2.5, the concentration-response function used for total (all cause) mortality in people above 30 years of age implies a relative risk of 1,062 per 10 µg.m^{-3}. Thus, assuming linearity, an increase of 10 µg.m^{-3} of PM2.5 is associated with a 6,2% increase in total mortality in the total population considered.

2c) Mortality: the total mortality (incidence base) in the country for the year under analysis and for the population over 30 years of age is 10 deaths per 1000 inhabitants, so the number of deaths per grid are as shown.

2d) Premature Deaths: the number of deaths attributed to exposure to PM2.5 in each cell is obtained from:

Relative Risk (RR) = exp (β * concentration) = exp (0.0062 * concentration)

For cell 1: 1.097462

Attributable Fraction (AF) = (RR-1) / RR

For cell 1: 0.0888065

Premature Deaths (PD) = AF * mortality * population

For cell 1: 8.88 ≈ 9

Uncertainty calculation:

3) Uncertainty: the uncertainty range is calculated using the lower (1.040) and upper (1.083) limits of the relative risk of PM2.5, instead of 1.062.

The total mortality is then expressed as 15 premature deaths, with 95% confidence interval between 9 and 20.

Figure 4. Health impact assessment scheme. Example for PM2.5, long-term exposure, all cause (natural) mortality, using WHO 2013 methodology (adapted from [55]).

The main objective of the first step, the population exposure assessment, is to cross gridded pollutant concentration maps with gridded population data, at the same spatial resolution, resulting in a map with the population exposed, by grid cell, to the selected pollutant. For that, in the present work, the following data were used:

- CAMx surface concentrations results for PM2.5, NO_2 and O_3, by grid cell, for each period analyzed (steps 1a and 1b in Figure 4 scheme);
- Most recent population data stratified by age and sex, from Census 2021, by the Portuguese national institute for statistics (INE) [57], for recent past, and INE projection for 2050 [58] for the future, spatially disaggregated according to the CAMx grid (step 1c in Figure 4 scheme).

In the second step, health risk estimation, relative risk data from epidemiological studies and incidence mortality statistics are used, together with population exposed from step 1, in order to assess the number of premature deaths, by grid cell, as shown in steps 2a to 2d in Figure 4 scheme. To apply it to the current case study, the following input data were used:

- Portuguese annual total number of deaths broken down by age, cohort and sex, from the European mortality database [48] (step 2c in Figure 4 scheme);
- Baseline concentration (C_0) and concentration-response functions (CRF) were used for the estimation of the relative risk (RR) (2a and 2b from Figure 4 scheme). For that, due to the recent update of the WHO air quality guidelines, two different methodologies were used: (i) the so called WHO 2013, according to the recommendations of HRAPIE [59] and REVIHAAP [53] projects, considering CRF from Jerrett et al. [60] for O_3 and from Hoek et al. [61] for PM2.5 and NO_2; and (ii) the so called WHO 2021, according to the recommendations of new WHO air quality guidelines [6], considering CRF from Chen and Hoek [62] for PM2.5 and Huangfu and Atkinson [63] for O_3 and NO_2. Table 1 presents detailed information on the CRFs used, as well as source of mortality data and C_0. From Table 1, major differences between WHO 2013 and WHO 2021 CRF methodologies can be found for mortality health outcomes associated with PM2.5 and NO_2 long-term exposure. For PM2.5, WHO 2021 considers a higher relative risk then WHO 2013. According to WHO 2021 methodology, an increase in 10 $\mu g.m^{-3}$ of PM2.5 is associated with a 8% increase in total mortality [61], while in WHO 2013 the increase in total mortality was only 6.2% [62]. However, WHO 2021 assumes a PM2.5 baseline concentration of 5 $\mu g.m^{-3}$, bellow which no health effects are expected, while WHO 2013 assumes expected health effects no matter the magnitude of PM2.5 concentrations. For NO_2 the opposite happens, with a decrease in the relative risk from 5.5%[61] in WHO 2013 to 2% [63] in WHO 2021, and the assumption that lower concentrations (above 10 $\mu g.m^{-3}$, rather than above 20 $\mu g.m^{-3}$ in WHO 2013) may have health impacts . The new baseline concentrations were determined by WHO [6], using the average of the five lowest 5th percentile levels measured in five selected studies for PM2.5 [64–68] and NO_2 [69–73].

Table 1. CRF used according to the WHO 2013 [53,59] and WHO 2021 [6] recommendations.

Pollutant	RR per 10 $\mu g.m^{-3}$ (95% CI)		Baseline Concentration (C_0)		Source of mortality data	Health outcome
	WHO 2013	WHO 2021	WHO 2013	WHO 2021		
PM2.5, annual mean	1.062 (1.040; 1.083), in [61]	1.08 (1.06; 1.09), in [62]	> 0 $\mu g.m^{-3}$	> 5 $\mu g.m^{-3}$	European mortality database in [74], ICD-10: A-R	Mortality, all-cause (natural), age 30+ years
NO_2, annual mean	1.055 (1.031; 1.080), in [61]	1.02 (1.01; 1.04), in [63]	> 20 $\mu g.m^{-3}$	> 10 $\mu g.m^{-3}$		
O_3, SOMO35 [1]	1.014 (1.005; 1.024), in [60]	1.01 (1.00; 1.02), in [63]	> 70 $\mu g.m^{-3}$	> 70 $\mu g.m^{-3}$	European mortality database in [74], ICD-10: J00-J99	Mortality, respiratory diseases, age 30+ years

[1] Summer months (April–September), average of daily maximum 8-hour mean over 35 ppb.

In step three, the uncertainty associated to the health risk estimation is calculated. Most of the uncertainty is related to the CRF used, since it derives from the assumptions made in epidemiological studies that take into account other confounding factors that can also have an impact on mortality (e.g., smoking, diet, lifestyle) [56]. Thus, following the EEA approach [54], the uncertainty is calculated using a 95 % confidence interval, indicating that there is 95 % probability that the true value lies in the range defined by the interval.

Finally, after the population exposure assessment, the health risk estimation and the uncertainty calculation, the total mortality due to PM2.5, NO_2 and O_3 long-term exposure was assessed.

3.2. *Results and Discussion*

Premature deaths, due to PM2.5, NO_2 and O_3 long-term exposure, for the mid-term future climate, the recent past climate, and the difference between them, considering both WHO 2013 and WHO 2021 CRF methodologies, are shown in Table 2.

Table 2. Premature deaths, due to PM2.5, NO_2 and O_3 long-term exposure, for the medium-term future climate (2055), recent past climate (2014) and the difference between them (2055 – 2014), considering both WHO 2013 and WHO 2021 CRF methodologies. Premature deaths considering the 95% confidence interval are shown in brackets. Note that negative values mean avoided premature deaths.

Pollutant	Health outcome	WHO 2013			WHO 2021		
		Future	Recent past	Difference	Future	Recent past	Difference
PM2.5, annual mean	Mortality, all-cause (natural), age 30+ years	3297 (1914; 4836)	6945 (3864; 9767)	-3648 (-1950; -4931)	93 (49; 109)	2234 (1579; 2546)	-2141 (-1530; -2437)
NO_2, annual mean		0 (0; 0)	13 (6; 21)	-13 (-6; -21)	0 (0; 0)	241 (83; 560)	-241 (-83; -560)
O_3, SOMO35	Mortality, respiratory diseases, age 30+ years	0 (0; 0)	0 (0; 0)	0 (0; 0)	0 (0; 0)	0 (0; 0)	0 (0; 0)

When considering the WHO 2013 CRF methodology, PM2.5 long-term exposure led to 3297 (95% CI: 1914 to 48369) and 6945 (95% CI: 3864 to 9767) premature deaths in the medium-term future and recent past climate, respectively, representing around 53% premature deaths avoided in the future. For NO_2, 13 premature deaths, with a 95% CI between 6 and 21, are estimated for the recent past climate and no premature deaths are expected for the future. If the WHO 2021 CRF methodology is considered, PM2.5 long-term exposure led to 93 (95% CI: 49 to 109) premature deaths in the medium-term future, meaning around premature deaths avoided, when compared with the 2234 (95% CI: 1579 to 2546) premature deaths found in the recent past. For NO_2, 241 premature deaths are estimated in the recent past climate, with a 95% CI between 83 and 560, and, as for WHO 2013 CRF methodology, no premature deaths are expected for the future. For both CRF methodologies and periods considered, O_3 long-term exposure will not result in premature deaths. Regardless of the CRF methodology used, there will be a reduction in the number of premature deaths related to PM2.5 and NO_2 long-term exposure, due to the projected air quality improvement for the medium-term future. However, premature deaths will also continue to occur in the future, due to long-term exposure of PM2.5 pollution, even if in a smaller number. From Table 2 it can be also concluded that the use of different CRF methodologies could substantially impact the estimated number of premature deaths. When considering WHO 2021 methodology, the changes in the relative risk and baseline concentration used will significatively impact the estimation of the health risk and, consequently the number of premature deaths. For PM2.5, although there is an increase in the relative risk, the reduction of the considered range concentrations from all to only above 5 $\mu g.m^{-3}$, associated with the baseline concentration used, led to a reduction in the number of premature deaths. However, for NO_2, the opposite is verified, with an increase in the premature deaths, mainly due to the change in the baseline concentration. Also, the confidence interval shows some changes, with a small range between the lower and upper values of premature deaths, due to the changes in the lower and upper values of the relative risk considered.

To better understand where the premature deaths are expected to occur, maps of mortality due to NO_2 and PM2.5 long-term exposure were also produced and are presented in Figure 5. For the two periods and CRF methodologies considered, O_3 mortality maps were not drawn as no premature deaths were obtained.

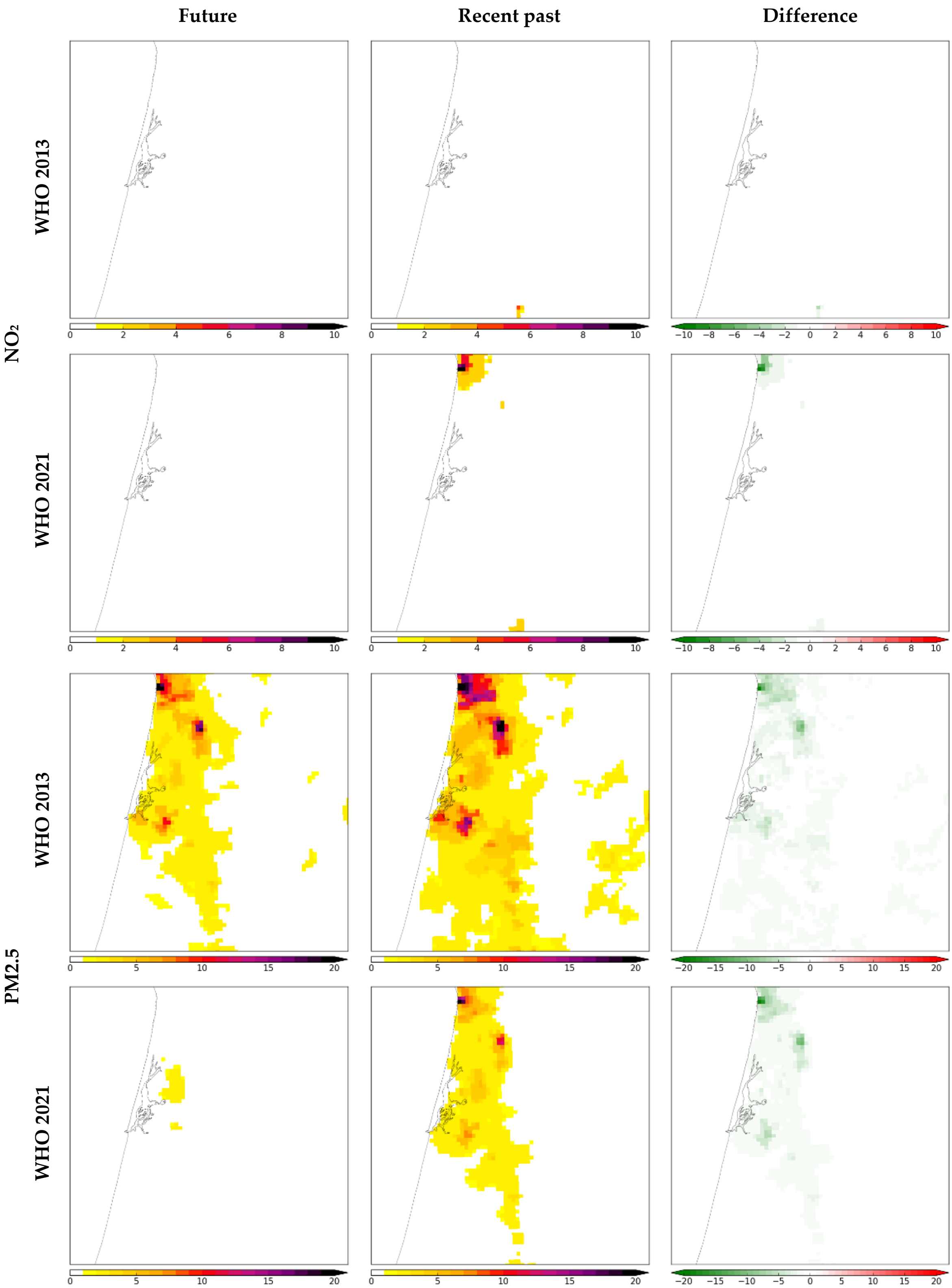


Figure 5. Mortality due to NO_2 and PM2.5 long-term exposure, expressed in number of premature deaths, for the medium-term future climate (2055), recent past climate (2014) and the difference between them (2055 – 2014), considering both WHO 2013 and WHO 2021 CRF methodologies. Note that negative values mean avoided premature deaths.

The projected premature deaths associated to NO_2 and PM2.5 show similar spatial patterns for medium-term future climate and recent past climate, but with different magnitudes of values. According to Figure 5, premature deaths are mostly obtained near the coastline, where the population density is higher, with special relevance in Porto metropolitan area, in the North of the domain, but also in high industrialized areas, as the one in Aveiro Region, where higher pollutant concentrations were previously obtained. Regarding the effects of the CRF methodology used in the spatial distribution of the premature deaths, this is more evident for NO_2. When using WHO 2021 methodology, with the reduction of the baseline concentration value, the relevance of NO_2 concentrations in urban areas is highlighted, as shown in Figure 5, where premature deaths are foreseen in the Porto metropolitan area. The same is not true when the WHO 2013 methodology is used. As already analysed in Table 2, regardless of the CRF methodology used, in the medium-term future climate there will be a reduction in the number of premature deaths related to both NO_2 and PM2.5 long-term exposure. For the recent past climate, these results are in line with those obtained by EEA [75].

4. Conclusions

In this work, the WRF-CAMx modelling system, followed by an health impact assessment, was applied to the Aveiro Region urban area, in Central Portugal. Climate change results for the medium-term future climate, when compared with the recent past climate, project higher mean temperature and lower total precipitation for the Aveiro Region. Despite these results, general improvements in air quality are foreseen, with no exceedances to the EU air quality limited values, mainly due to the reduction in future emissions imposed by the European legislation. Nonetheless, some concerns regarding PM2.5 and O_3 concentrations remain when the new WHO air quality recommendation levels are considered. Following the air quality trend, also mortality due to pollutants long-term exposure will decrease, with only premature deaths related to PM2.5 pollution being expected, regardless the CRF methodology used (WHO 2013 or WHO 2021).

Although this joint analysis of climate change, air quality and health impacts give valuable information on these research fields, some limitations can be identified, and caution should be taken in using these results. As for all studies based on numerical modeling, uncertainties resulting from the modelling formulations and parameterizations, the input data (e.g. meteorology, emission inventories, population data), the CRF methodology, as well as the spatial resolution used, can affect the model results accuracy and also the reliability of the health impact assessment. Also, land use patterns will be influenced by climate change, and will impact on emissions and, consequently, on air quality, thus land use changes should be considered in future works.

Moreover, this study allowed to conclude that the use of different CRF methodologies in the health impact assessment could substantially impact the number of premature deaths. This evidence the magnitude of uncertainty related to the estimation of health impacts of air pollution, and reinforces the need for an adequate awareness when communicating this type of scientific results to stakeholders and the general population.

Notwithstanding, the methodology applied in this work constitutes an added value in this research field, providing valuable information for policy makers and helping citizens increasing awareness about climate change, air pollution and human health impacts. Furthermore, both modelling and epidemiologist scientific communities may apply the developed methodology in other areas and benefit from the advances in the harmonization between climate change, air quality and health impact assessments for urban areas.

Author Contributions: Conceptualization and methodology, S.C. and J.F; formal analysis, investigation, and writing—original draft preparation, S.C.; writing—review and editing, J.F, D.C and M.L; supervision, J.F and M.L. All authors have read and agreed to the published version of the manuscript.

Funding: Thanks are due to the financial support to the PhD grant of S. Coelho (SFRH/BD/137999/2018), the contract grants of J. Ferreira (2020.00622.CEECIND) and D. Carvalho (CEECIND/01726/2017), and to CESAM (UIDP/50017/2020+ UIDB/50017/2020+ LA/P/0094/2020), to

 doi:10.20944/preprints202209.0207.v1

FCT/MCTES through national funds and the co funding by the FEDER, within the PT2020 Partnership Agreement and Compete 2020.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The relevant data underlying this study are fully available under the details provided in the references. For further questions, please contact the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Figure A1 shows the seasonal mean temperature, in °C, for the medium-term future climate, recent past climate and the difference between them.

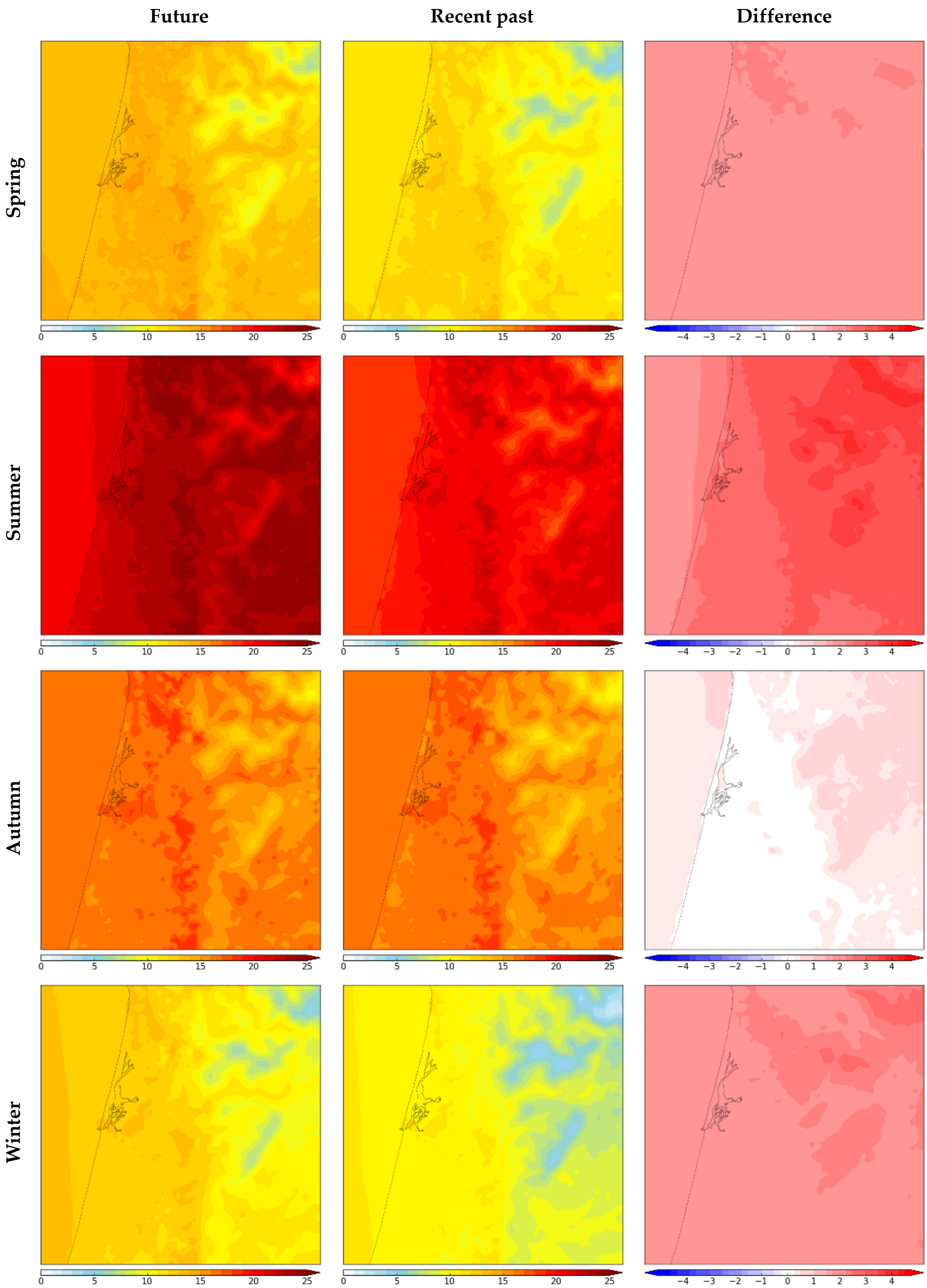


Figure A1. Seasonal average of mean temperature, in °C, for the medium-term future climate (2055), recent past climate (2014) and the difference between them (2055 – 2014).

Figure A2 shows the seasonal total precipitation, for the medium-term future climate, recent past climate, and the difference between them.

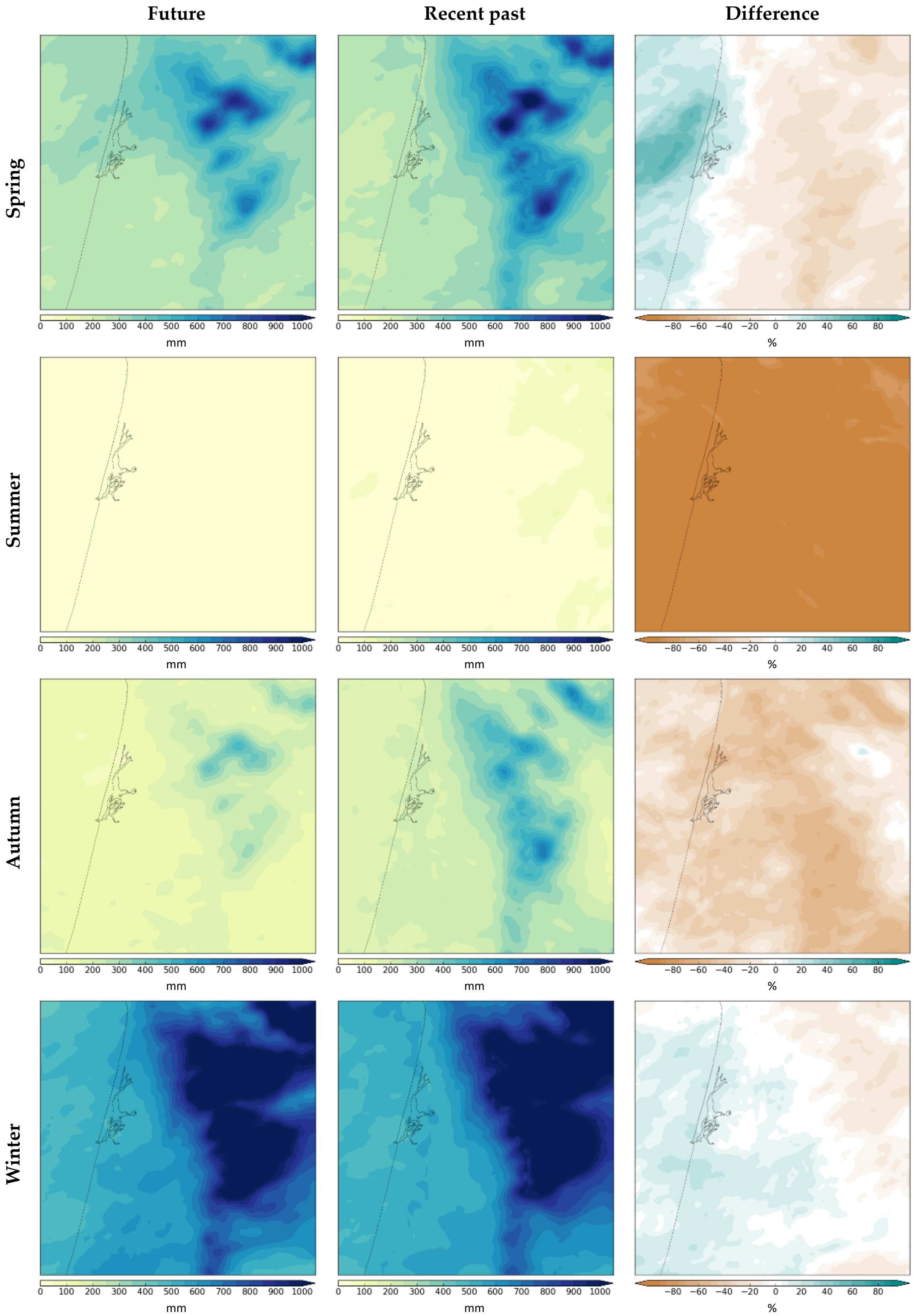


Figure A2. Seasonal total precipitation, for the medium-term future climate (2055), recent past climate (2014), in mm, and the difference between them (2055 – 2014), in %.

Figure A3 shows seasonal average concentrations of NO_2, for the medium-term future climate, recent past climate, and the difference between them.

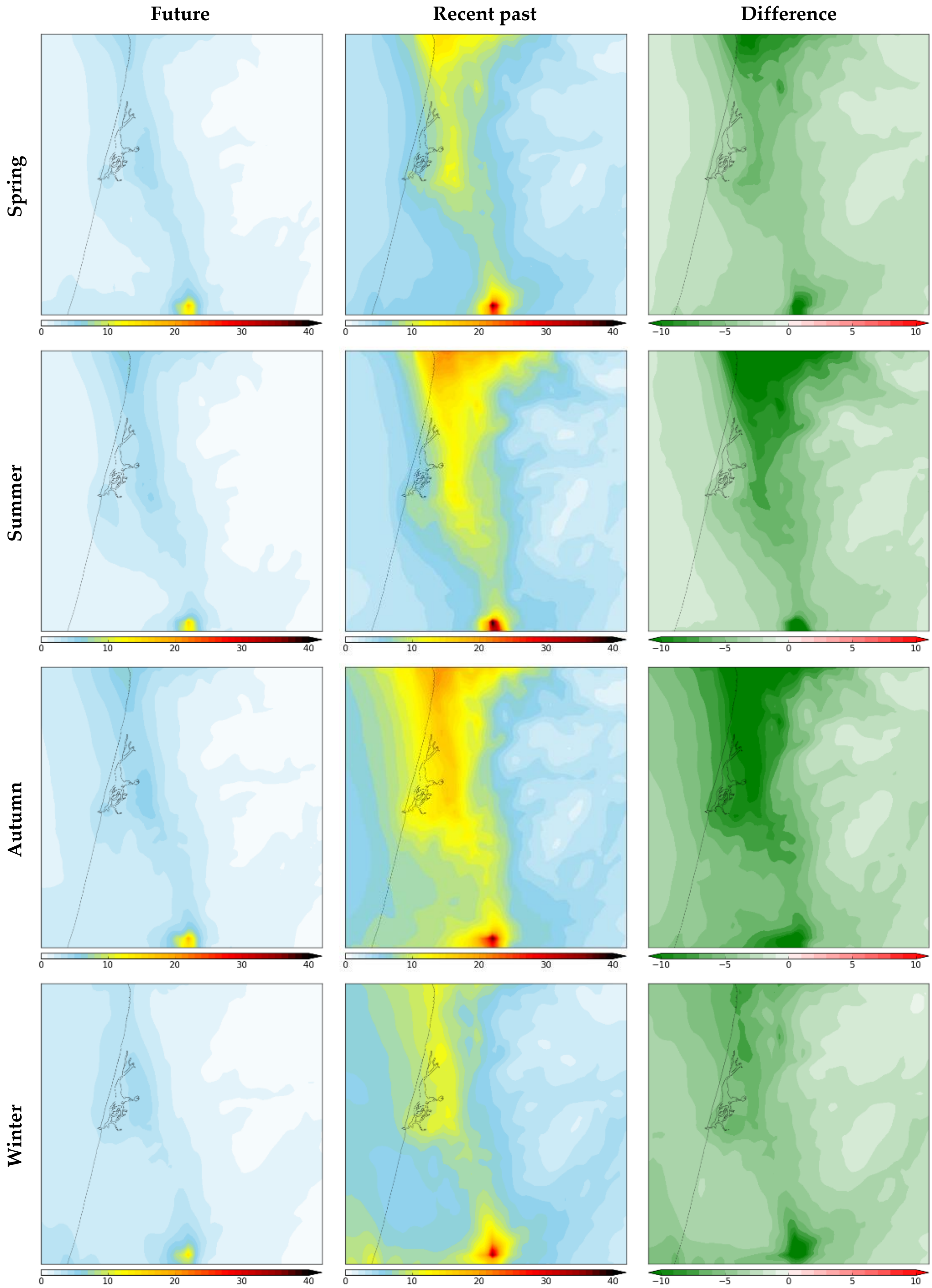


Figure A3. Seasonal average concentrations of NO_2, in $\mu g.m^{-3}$, for the medium-term future climate (2055), recent past climate (2014) and the difference between them (2055 – 2014). For future and recent past maps, the maximum value of the color scale represents the EU limit value (40 $\mu g.m^{-3}$).

Figure A4 shows seasonal average concentrations of the maximum daily 8 h mean O_3, for the medium-term future climate, recent past climate, and the difference between them.

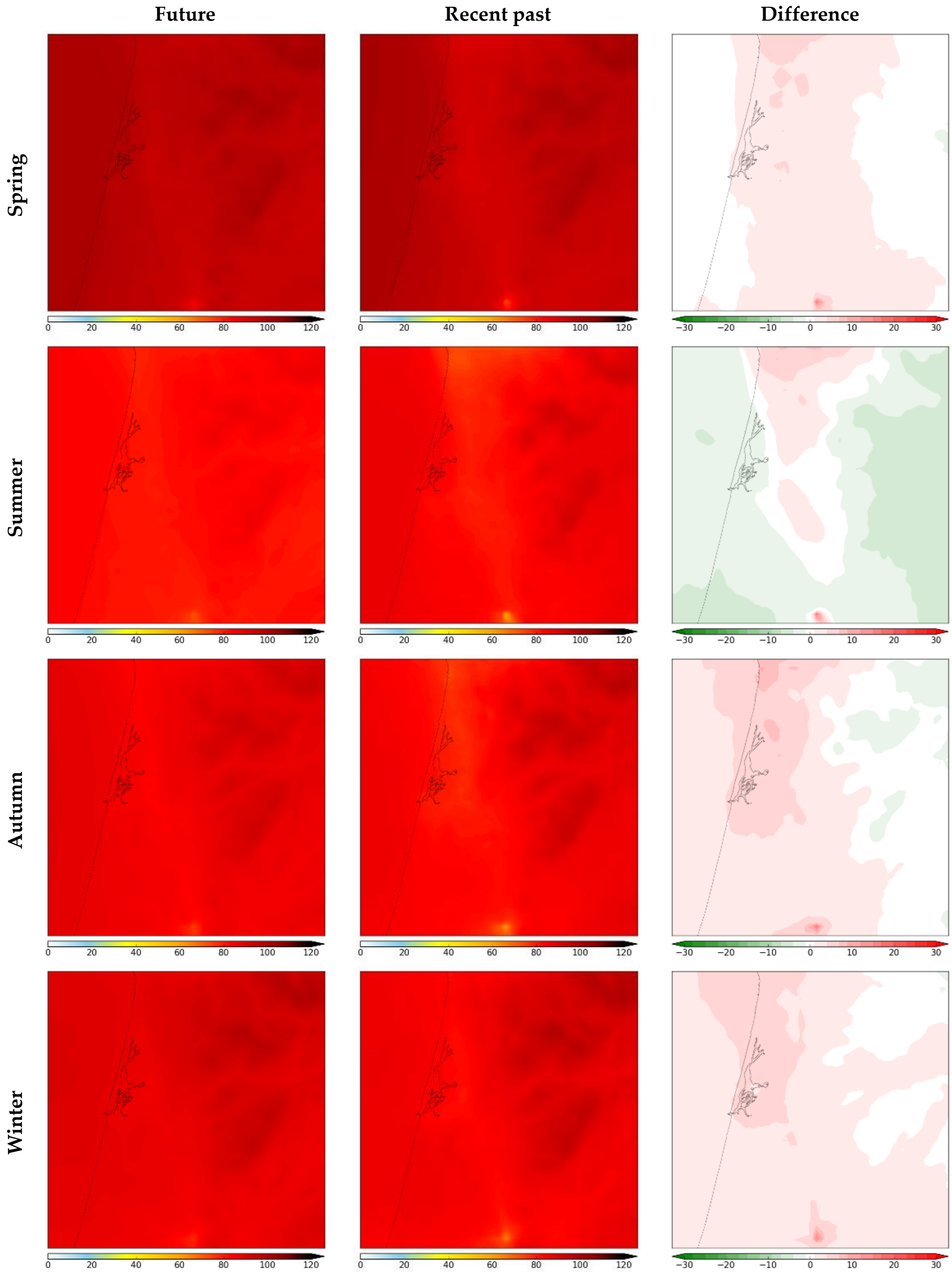


Figure A4. Seasonal average concentrations of the maximum daily 8 h mean O_3, in µg.m^{-3}, for the medium-term future climate (2055), recent past climate (2014) and the difference between them (2055 – 2014). For future and recent past maps, the maximum value of the color scale represents the EU target value (120 µg.m^{-3}).

 doi:10.20944/preprints202209.0207.v1

Figure A5 shows seasonal average concentrations of PM10, for the medium-term future climate, recent past climate, and the difference between them.

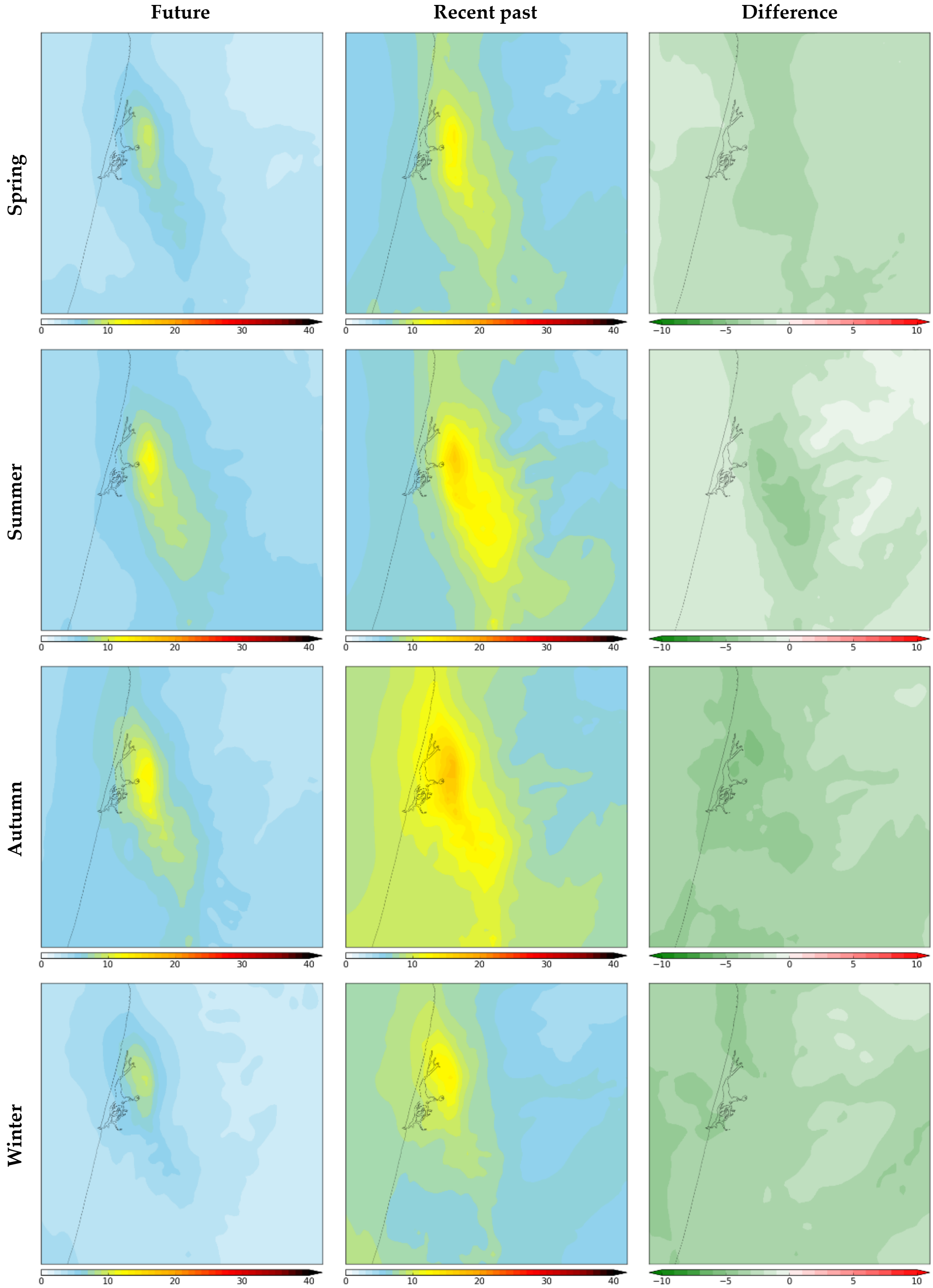


Figure A5. Seasonal average concentrations of PM10, in µg.m^{-3}, for the medium-term future climate (2055), recent past climate (2014) and the difference between them (2055 – 2014). For future and recent past maps, the maximum value of the color scale represents the EU limit value (40 µg.m^{-3}).

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 14 September 2022 doi:10.20944/preprints202209.0207.v1

Figure A6 shows seasonal average concentrations of PM2.5, for the medium-term future climate, recent past climate, and the difference between them.

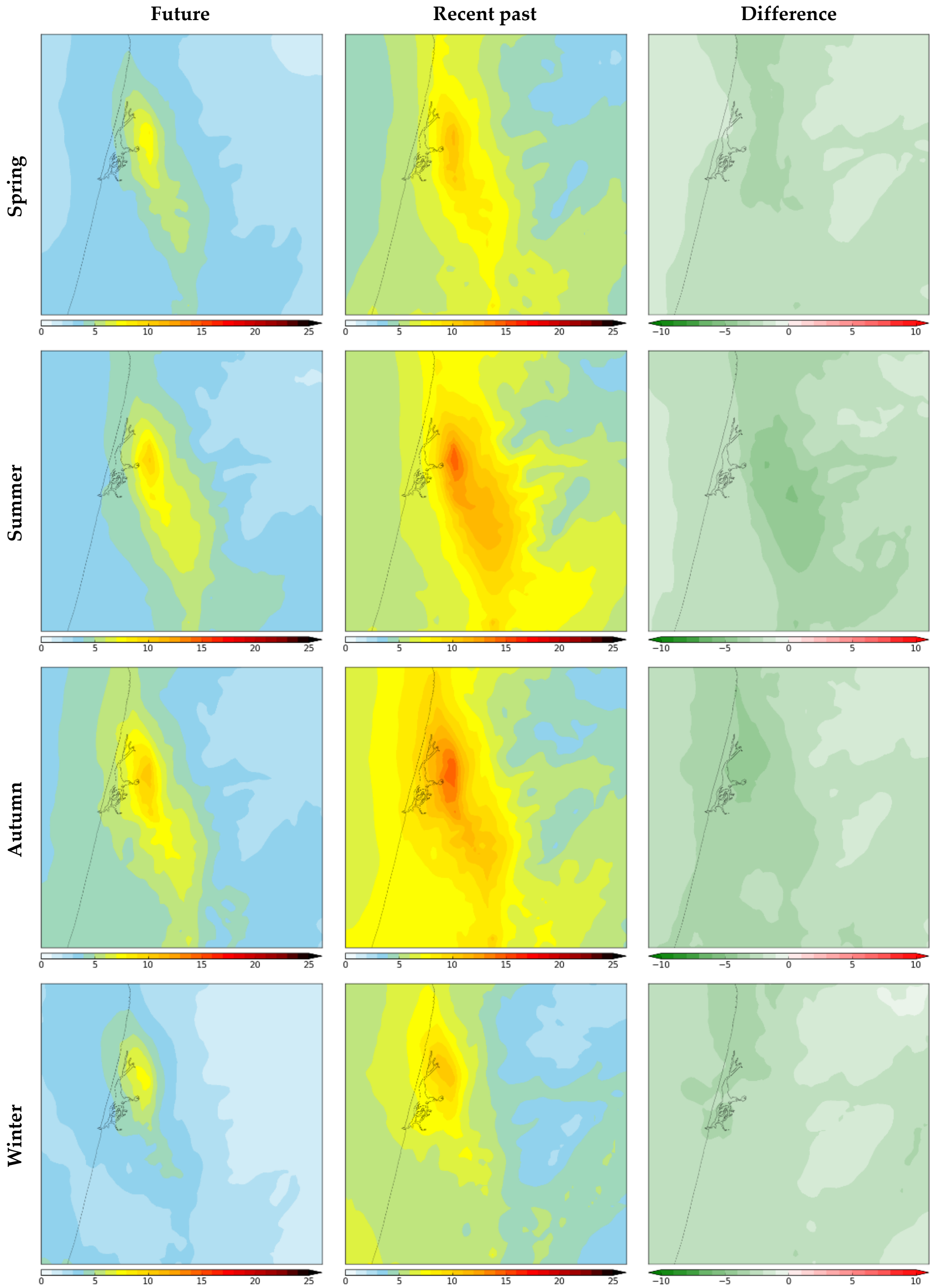


Figure A6. Seasonal average concentrations of PM2.5, in µg.m^{-3}, for the medium-term future climate (2055), recent past climate (2014) and the difference between them (2055 – 2014). For future and recent past maps, the maximum value of the color scale represents the EU limit value (25 µg.m^{-3}).

References

1. Grossberndt, S.; Bartonova, A.; Ortiz, A.G. *Public Awareness and Efforts to Improve Air Quality in Europe — Eionet Report - ETC/ATNI 2020/2*; 2021;
2. Von Schneidemesser, E.; Monks, P.S.P.S.; Allan, J.D.J.D.; Bruhwiler, L.; Forster, P.; Fowler, D.; Lauer, A.; Morgan, W.T.W.T.; Paasonen, P.; Righi, M.; et al. Chemistry and the Linkages between Air Quality and Climate Change. *Chem. Rev.* **2015**, *115*, 3856–3897, doi:10.1021/acs.chemrev.5b00089.
3. Eurostat *Urban Europe: Statistics on Cities, Towns and Suburbs - 2016 Edition*; Publications office of the European Union: Luxembourg, 2016;
4. EEA Exceedance of Air Quality Standards in Europe Available online: https://www.eea.europa.eu/ims/exceedance-of-air-quality-standards#footnote-RWRZZSXA (accessed on 29 August 2022).
5. EC Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on Ambient Air Quality and Cleaner Air for Europe. *Eur. Comm. - Off. J. Eur. Union* **2008**, *L 152 (EN)*.
6. WHO *WHO Global Air Quality Guidelines: Particulate Matter (PM2.5 and PM10), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide*; 2021;
7. EC *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions - "A Clean Air Programme for Europe"*; Brussels, 2013;
8. EC *Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions - "The European Green Deal"*; Brussels, 2019;
9. WHO *World Health Statistics 2022: Monitoring Health for the SDGs, Sustainable Development Goals*; World Health Organization: Geneva, Switzerland, 2022;
10. EEA *Air Quality in Europe 2021 - European Environmental Agency Report No 15/2021*; Luxembourg, 2021;
11. Seo, J.; Kim, J.Y.; Youn, D.; Lee, J.Y.; Kim, H.; Lim, Y. Bin; Kim, Y.; Jin, H.C. On the Multiday Haze in the Asian Continental Outflow: The Important Role of Synoptic Conditions Combined with Regional and Local Sources. *Atmos. Chem. Phys.* **2017**, *17*, 9311–9332, doi:10.5194/acp-17-9311-2017.
12. Coelho, S.; Rafael, S.; Lopes, D.; Miranda, A.I.; Ferreira, J. How Changing Climate May Influence Air Pollution Control Strategies for 2030? *Sci. Total Environ.* **2021**, *758*, doi:10.1016/j.scitotenv.2020.143911.
13. IPCC *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, B. Zhou, Eds.; Cambridge University Press (in press), 2021;
14. Revi, A.; Satterthwaite, D..; Aragón-Durand, F.; Corfee-Morlot, J.; Kiunsi, R.B.R.; Pelling, M.; Roberts, D.C.; Solecki, W. Urban Areas. In *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L., Eds.; Cambridge University Press: Cambridge, UK and New York, NY, USA, 2014; pp. 535–612 ISBN 9781107415379.
15. Radhakrishnan, M.; Islam, T.; Ashley, R.M.; Pathirana, A.; Quan, N.H.; Gersonius, B.; Zevenbergen, C. Context Specific Adaptation Grammars for Climate Adaptation in Urban Areas. *Environ. Model. Softw.* **2018**, *102*, 73–83, doi:10.1016/j.envsoft.2017.12.016.
16. Radhakrishnan, M.; Pathirana, A.; Ashley, R.; Zevenbergen, C. Structuring Climate Adaptation through Multiple Perspectives: Framework and Case Study on Flood Risk Management. *Water* **2017**, *9*, 129, doi:10.3390/w9020129.
17. Coelho, S.; Ferreira, J.; Rodrigues, V.; Lopes, M. Source Apportionment of Air Pollution in European Urban Areas: Lessons from the ClairCity Project. *J. Environ. Manage.* **2022**, *320*, 115899, doi:10.1016/j.jenvman.2022.115899.
18. Jiang, Y.; Hou, L.; Shi, T.; Gui, Q. A Review of Urban Planning Research for Climate Change. *Sustainability* **2017**, *9*, 2224,

doi:10.3390/su9122224.
19. Rodrigues, V.; Gama, C.; Ascenso, A.; Oliveira, K.; Coelho, S.; Monteiro, A.; Hayes, E.; Lopes, M. Assessing Air Pollution in European Cities to Support a Citizen Centered Approach to Air Quality Management. *Sci. Total Environ.* **2021**, *799*, 149311, doi:10.1016/j.scitotenv.2021.149311.
20. Coelho, S.; Rodrigues, V.; Barnes, J.; Boushel, C.; Devito, L.; Lopes, M. Air Pollution in the Aveiro Region, Portugal: A Citizens' Engagement Approach. *WIT Trans. Ecol. Environ.* **2018**, *230*, 253–262, doi:10.2495/AIR180241.
21. Slingerland, S.; Artola, I.; Lopes, M.; Rodrigues, V.; Borrego, C.; Miranda, A.I.; Silva, S.; Coelho, S.; Cravo, O.; Matos, J.E. *D6.2 Air Quality and Climate Related Policies in the Intermunicipal Community of the Region of Aveiro (CIRA, Portugal) – Baseline Analysis*; Rotterdam, Netherlands, 2018;
22. Peel, M.C.; Finlayson, B.L.; McMahon, T.A. Updated World Map of the Köppen-Geiger Climate Classification. *Hydrol. Earth Syst. Sci.* **2007**, *11*, 1633–1644, doi:10.5194/hess-11-1633-2007.
23. Skamarock, W.C.; Klemp, J.B.; Dudhia, J.; Gill, D.O.; Liu, Z.; Berner, J.; Wang, W.; Powers, J.G.; Duda, M.G.; Barker, D.M.; et al. *A Description of the Advanced Research WRF Version 4. NCAR Tech. Note NCAR/TN-556+STR*; Boulder, Colorado, USA, 2019;
24. ENVIRON *CAMx. User's Guide. Comprehensive Air Quality Model with Extensions. Version 7.10*; 2020;
25. Ferreira, J.; Lopes, D.; Rafael, S.; Relvas, H.; Almeida, S.M.; Miranda, A.I. Modelling Air Quality Levels of Regulated Metals: Limitations and Challenges. *Environ. Sci. Pollut. Res.* **2020**, *27*, 33916–33928, doi:10.1007/S11356-020-09645-9/FIGURES/10.
26. Mauritsen, T.; Bader, J.; Becker, T.; Behrens, J.; Bittner, M.; Brokopf, R.; Brovkin, V.; Claussen, M.; Crueger, T.; Esch, M.; et al. Developments in the MPI-M Earth System Model Version 1.2 (MPI-ESM1.2) and Its Response to Increasing CO2. *J. Adv. Model. Earth Syst.* **2019**, *11*, 998–1038, doi:10.1029/2018MS001400.
27. Brands, S.; Herrera, S.; Fernández, J.; Gutiérrez, J.M. How Well Do CMIP5 Earth System Models Simulate Present Climate Conditions in Europe and Africa? *Clim. Dyn.* **2013**, *41*, 803–817, doi:10.1007/s00382-013-1742-8.
28. Marta-Almeida, M.; Teixeira, J.C.; Carvalho, M.J.; Melo-Gonçalves, P.; Rocha, A.M. High Resolution WRF Climatic Simulations for the Iberian Peninsula: Model Validation. *Phys. Chem. Earth, Parts A/B/C* **2016**, *94*, 94–105, doi:10.1016/j.pce.2016.03.010.
29. Rafael, S.; Martins, H.; Marta-Almeida, M.; Sá, E.; Coelho, S.; Rocha, A.; Borrego, C.; Lopes, M. Quantification and Mapping of Urban Fluxes under Climate Change: Application of WRF-SUEWS Model to Greater Porto Area (Portugal). *Environ. Res.* **2017**, *155*, 321–334, doi:10.1016/j.envres.2017.02.033.
30. Coelho, S.; Rafael, S.; Coutinho, M.; Monteiro, A.; Medina, J.; Figueiredo, S.; Cunha, S.; Lopes, M.; Miranda, A.I.A.I.; Borrego, C. Climate-Change Adaptation Framework for Multiple Urban Areas in Northern Portugal. *Environ. Manage.* **2020**, *66*, 1–12, doi:10.1007/s00267-020-01313-5.
31. Coelho, S.; Rafael., S.; Fernandes, A.P.; Lopes, M.; Carvalho, D. How the New Climate Scenarios Will Affect Air Quality Trends: An Exploratory Research. *Urban Clim.* (under review).
32. Hong, S.; Lim, S. The WRF Single-Moment 6-Class Microphysics Scheme (WSM6). *J. Korean Meteorol. Soc.* **2006**, *42*, 129–151.
33. Iacono, M.J.; Delamere, J.S.; Mlawer, E.J.; Shephard, M.W.; Clough, S.A.; Collins, W.D. Radiative Forcing by Long-Lived Greenhouse Gases: Calculations with the AER Radiative Transfer Models. *J. Geophys. Res.* **2008**, *113*, D13103, doi:10.1029/2008JD009944.
34. Jiménez, P.A.; Dudhia, J.; González-Rouco, J.F.; Navarro, J.; Montávez, J.P.; García-Bustamante, E. A Revised Scheme for the WRF Surface Layer Formulation. *Mon. Weather Rev.* **2012**, *140*, 898–918, doi:10.1175/MWR-D-11-00056.1.
35. Tewari, M.; Chen, F.; Wang, W.; Dudhia, J.; LeMone, M.A.A.; Mitchell, K.; Ek, M.; Gayno, G.; Wegiel, J.; Cuence, R..; et al. Implementation and Verification of the Unified NOAH Land Surface Model in the WRF Model. In Proceedings of the 20th Conference on Weather Analysis and Forecasting/16th Conference on Numerical Weather Prediction; 2004; pp. 11–15.
36. Hong, S.-Y.; Noh, Y.; Dudhia, J. A New Vertical Diffusion Package with an Explicit Treatment of Entrainment Processes. *Mon. Weather Rev.* **2006**, doi:10.1175/MWR3199.1.
37. Grell, G.A.; Freitas, S.R. A Scale and Aerosol Aware Stochastic Convective Parameterization for Weather and Air Quality

Modeling. *Atmos. Chem. Phys.* **2014**, *14*, 5233–5250, doi:10.5194/ACP-14-5233-2014.
38. Ascenso, A.; Augusto, B.; Silveira, C.; Rafael, S.; Coelho, S.; Monteiro, A.; Ferreira, J.; Menezes, I.; Roebeling, P.; Miranda, A.I. Impacts of Nature-Based Solutions on the Urban Atmospheric Environment: A Case Study for Eindhoven, The Netherlands. *Urban For. Urban Green.* **2021**, *57*, 126870, doi:10.1016/j.ufug.2020.126870.
39. Wang, X.Y.; Wang, K.C. Estimation of Atmospheric Mixing Layer Height from Radiosonde Data. *Atmos. Meas. Tech.* **2014**, *7*, 1701–1709, doi:10.5194/amt-7-1701-2014.
40. Kayes, I.; Shahriar, S.A.; Hasan, K.; Akhter, M.; Kabir, M.M.; Salam, M.A. The Relationships between Meteorological Parameters and Air Pollutants in an Urban Environment. *Glob. J. Environ. Sci. Manag.* **2019**, *5*, 265–278, doi:10.22034/gjesm.2019.03.01.
41. Aw, J.; Kleeman, M.J. Evaluating the First-Order Effect of Intraannual Temperature Variability on Urban Air Pollution. *J. Geophys. Res. Atmos.* **2003**, *108*, doi:10.1029/2002jd002688.
42. Jacob, D.J.; Winner, D.A. Effect of Climate Change on Air Quality. *Atmos. Environ.* **2009**, *43*, 51–63, doi:10.1016/j.atmosenv.2008.09.051.
43. Fricko, O.; Havlik, P.; Rogelj, J.; Klimont, Z.; Gusti, M.; Johnson, N.; Kolp, P.; Strubegger, M.; Valin, H.; Amann, M.; et al. The Marker Quantification of the Shared Socioeconomic Pathway 2: A Middle-of-the-Road Scenario for the 21st Century. *Glob. Environ. Chang.* **2017**, *42*, 251–267, doi:10.1016/J.GLOENVCHA.2016.06.004.
44. Riahi, K.; van Vuuren, D.P.; Kriegler, E.; Edmonds, J.; O'Neill, B.C.; Fujimori, S.; Bauer, N.; Calvin, K.; Dellink, R.; Fricko, O.; et al. The Shared Socioeconomic Pathways and Their Energy, Land Use, and Greenhouse Gas Emissions Implications: An Overview. *Glob. Environ. Chang.* **2017**, *42*, 153–168, doi:10.1016/j.gloenvcha.2016.05.009.
45. Emmons, L.K.; Schwantes, R.H.; Orlando, J.J.; Tyndall, G.; Kinnison, D.; Lamarque, J.-F.; Marsh, D.; Mills, M.J.; Tilmes, S.; Bardeen, C.; et al. The Chemistry Mechanism in the Community Earth System Model Version 2 (CESM2). *J. Adv. Model. Earth Syst.* **2020**, *12*, e2019MS001882, doi:10.1029/2019MS001882.
46. EMEP European Monitoring and Evaluation Programme. Http://Www.Emep.Int/.
47. Yarwood, G.; Jung, J.; Whitten, G.Z.; Heo, G.; Mellberg, J.; Estes, M. Updates to the Carbon Bond Mechanism for Version 6 (CB6). In Proceedings of the 9th Annual CMAS Conference; Chapel Hill, NC, 2010.
48. Sá, E.; Ferreira, J.; Carvalho, A.; Borrego, C. Development of Current and Future Pollutant Emissions for Portugal. *Atmos. Pollut. Res.* **2015**, *6*, 849–857, doi:10.5094/APR.2015.094.
49. Monjardino, J.; Dias, L.; Vale, G.; Tente, H.; Gouveia, J.P.; Barroso, J.E.; Dias, L.; Aires, N.; Fortes, P.; Ferreira, F.; et al. *Relatório Setorial: Estimativa de Poluentes Atmosféricos. Trabalhos de Base Para o Roteiro Para a Neutralidade Carbónica 2050*; Portugal, 2019;
50. Vicente-Serrano, S.M.; Lopez-Moreno, J.-I.; Beguería, S.; Lorenzo-Lacruz, J.; Sanchez-Lorenzo, A.; García-Ruiz, J.M.; Azorin-Molina, C.; Morán-Tejeda, E.; Revuelto, J.; Trigo, R.; et al. Evidence of Increasing Drought Severity Caused by Temperature Rise in Southern Europe. *Environ. Res. Lett.* **2014**, *9*, 044001, doi:10.1088/1748-9326/9/4/044001.
51. Duhanyan, N.; Roustan, Y. Below-Cloud Scavenging by Rain of Atmospheric Gases and Particulates. *Atmos. Environ.* **2011**, *45*, 7201–7217, doi:10.1016/j.atmosenv.2011.09.002.
52. Guo, L.-C.; Zhang, Y.; Lin, H.; Zeng, W.; Liu, T.; Xiao, J.; Rutherford, S.; You, J.; Ma, W. The Washout Effects of Rainfall on Atmospheric Particulate Pollution in Two Chinese Cities. *Environ. Pollut.* **2016**, *215*, 195–202, doi:10.1016/j.envpol.2016.05.003.
53. WHO *Review of Evidence on Health Aspects of Air Pollution - REVIHAAP Project, Technical Report*; 2013;
54. Soares, J.; Horálek, J.; Ortiz, A.G.; Guerreiro, C.; Gsella, A. *ETC/ATNI Report 13/2019: Health Risk Assessment of Air Pollution in Europe. Methodology Description and 2017 Results.*; Kjeller, Norway, 2019;
55. EEA *Assessing the Risks to Health from Air Pollution. Briefing No. 11/2018.*; 2018;
56. WHO *Health Risk Assessment of Air Pollution - General Principles*; Copenhagen, Denmark, 2016;
57. INE Resident Population (No.) by Place of Residence, Sex and Age Group; Decennial - Statistics Portugal, Population and Housing Census - 2021 Available online: https://www.ine.pt/xportal/xmain?xpid=INE&xpgid=ine_indicadores&indOcorrCod=0011166&contexto=bd&selTab=tab2

(accessed on 28 July 2022).
58. INE Resident Population (Projections 2015-2080 - No.) by Place of Residence (NUTS - 2013), Sex, Age and Scenario; Annual - Statistics Portugal, Resident Population Projections Available online: https://www.ine.pt/xportal/xmain?xpid=INE&xpgid=ine_indicadores&indOcorrCod=0009098&contexto=bd&selTab=tab2.
59. WHO *Health Risks of Air Pollution in Europe – HRAPIE Project: Recommendations for Concentration–Response Functions for Cost–Benefit Analysis of Particulate Matter, Ozone and Nitrogen Dioxide*; Copenhagen, Denmark, 2013;
60. Jerrett, M.; Burnett, R.T.; Pope, C.A.; Ito, K.; Thurston, G.; Krewski, D.; Shi, Y.; Calle, E.; Thun, M. Long-Term Ozone Exposure and Mortality. *N. Engl. J. Med.* **2009**, *360*, 1085–1095, doi:10.1056/NEJMOA0803894/SUPPL_FILE/NEJM_JERRETT_1085SA1.PDF.
61. Hoek, G.; Krishnan, R.M.; Beelen, R.; Peters, A.; Ostro, B.; Brunekreef, B.; Kaufman, J.D. Long-Term Air Pollution Exposure and Cardio-Respiratory Mortality: A Review. *Environ. Heal. A Glob. Access Sci. Source* **2013**, *12*, 1–16, doi:10.1186/1476-069X-12-43/TABLES/6.
62. Chen, J.; Hoek, G. Long-Term Exposure to PM and All-Cause and Cause-Specific Mortality: A Systematic Review and Meta-Analysis. *Environ. Int.* **2020**, *143*, doi:10.1016/J.ENVINT.2020.105974.
63. Huangfu, P.; Atkinson, R. Long-Term Exposure to NO2 and O3 and All-Cause and Respiratory Mortality: A Systematic Review and Meta-Analysis. *Environ. Int.* **2020**, *144*, 105998, doi:10.1016/J.ENVINT.2020.105998.
64. Weichenthal, S.; Villeneuve, P.J.; Burnett, R.T.; van Donkelaar, A.; Martin, R. V.; Jones, R.R.; DellaValle, C.T.; Sandler, D.P.; Ward, M.H.; Hoppin, J.A. Long-Term Exposure to Fine Particulate Matter: Association with Nonaccidental and Cardiovascular Mortality in the Agricultural Health Study Cohort. *Environ. Health Perspect.* **2014**, *122*, 609–615, doi:10.1289/ehp.1307277.
65. Pinault, L.; Tjepkema, M.; Crouse, D.L.; Weichenthal, S.; Van Donkelaar, A.; Martin, R. V.; Brauer, M.; Chen, H.; Burnett, R.T. Risk Estimates of Mortality Attributed to Low Concentrations of Ambient Fine Particulate Matter in the Canadian Community Health Survey Cohort. *Environ. Heal. A Glob. Access Sci. Source* **2016**, *15*, 1–15, doi:10.1186/S12940-016-0111-6/FIGURES/2.
66. Pinault, L.L.; Weichenthal, S.; Crouse, D.L.; Brauer, M.; Erickson, A.; Donkelaar, A. van; Martin, R. V.; Hystad, P.; Chen, H.; Finès, P.; et al. Associations between Fine Particulate Matter and Mortality in the 2001 Canadian Census Health and Environment Cohort. *Environ. Res.* **2017**, *159*, 406–415, doi:10.1016/J.ENVRES.2017.08.037.
67. Cakmak, S.; Hebbern, C.; Pinault, L.; Lavigne, E.; Vanos, J.; Crouse, D.L.; Tjepkema, M. Associations between Long-Term PM 2.5 and Ozone Exposure and Mortality in the Canadian Census Health and Environment Cohort (CANCHEC), by Spatial Synoptic Classification Zone. *Environ. Int.* **2018**, *111*, 200–211, doi:10.1016/J.ENVINT.2017.11.030.
68. Villeneuve, P.J.; Weichenthal, S.A.; Crouse, D.; Miller, A.B.; To, T.; Martin, R. V.; Van Donkelaar, A.; Wall, C.; Burnett, R.T. Long-Term Exposure to Fine Particulate Matter Air Pollution and Mortality among Canadian Women. *Epidemiology* **2015**, *26*, 536–545, doi:10.1097/EDE.0000000000000294.
69. Tonne, C.; Wilkinson, P. Long-Term Exposure to Air Pollution Is Associated with Survival Following Acute Coronary Syndrome. *Eur. Heart J.* **2013**, *34*, 1306–1311, doi:10.1093/EURHEARTJ/EHS480.
70. Turner, M.C.; Jerrett, M.; Pope, C.A.; Krewski, D.; Gapstur, S.M.; Diver, W.R.; Beckerman, B.S.; Marshall, J.D.; Su, J.; Crouse, D.L.; et al. Long-Term Ozone Exposure and Mortality in a Large Prospective Study. *https://doi.org/10.1164/rccm.201508-1633OC* **2016**, *193*, 1134–1142, doi:10.1164/RCCM.201508-1633OC.
71. Hart, J.E.; Rimm, E.B.; Rexrode, K.M.; Laden, F. Changes in Traffic Exposure and the Risk of Incident Myocardial Infarction and All-Cause Mortality. *Epidemiology* **2013**, *24*, 734–742, doi:10.1097/EDE.0B013E31829D5DAE.
72. Carey, I.M.; Atkinson, R.W.; Kent, A.J.; Van Staa, T.; Cook, D.G.; Anderson, H.R. Mortality Associations with Long-Term Exposure to Outdoor Air Pollution in a National English Cohort. *Am. J. Respir. Crit. Care Med.* **2013**, *187*, 1226–1233, doi:10.1164/RCCM.201210-1758OC/SUPPL_FILE/DISCLOSURES.PDF.
73. Hart, J.E.; Garshick, E.; Dockery, D.W.; Smith, T.J.; Ryan, L.; Laden, F. Long-Term Ambient Multipollutant Exposures and

Mortality. *Am. J. Respir. Crit. Care Med.* **2011**, *183*, 73–78, doi:10.1164/RCCM.200912-1903OC.
74. WHO WHO Mortality Database Available online: https://www.who.int/data/data-collection-tools/who-mortality-database (accessed on 28 May 2022).
75. EEA *Air Quality in Europe : 2017 Report - European Environment Agency Report No 13/2017*; Luxembourg, 2017;