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# Ozone and heat-related mortality in Europe in 2050 significantly affected by changes in climate, population and greenhouse gas emission

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## Abstract

Climate change is expected to increase to extreme temperatures and lead to more intense formation of near-surface ozone. Higher temperatures can cause heat stress and ozone is a highly oxidative pollutant; both increase cardiorespiratory mortality. Using greenhouse gas and ozone precursor emission scenarios, global and regional climate and chemistry-transport models, epidemiological data, and population projections, we projected ozone- and heat-related health risks under a changing climate. European near-surface temperature was modelled with the regional climate model (RCA4), forced by the greenhouse gas emission scenario RCP4.5 and the global climate model EC-EARTH, and near-surface ozone was modelled with the Multi-scale Atmospheric Transport and Chemistry (MATCH) model. Two periods were compared: recent climate in 1991–2000 and future climate in 2046–2055, projecting around a 2° increase in global temperatures by that time. Projections of premature mortality considered future climate, future population, and future emissions separately and jointly to understand the relative importance of their contributions. Ozone currently causes 55 000 premature deaths annually in Europe due to long-term exposure, including a proportion of the estimated 26 000 deaths per year due to short-term exposures. When only taking into account the impact of a changing climate, up to an 11% increase in ozone-associated mortality is expected in some countries in Central and Southern Europe in 2050. However, projected decreases in ozone precursor emissions are expected to result in a decrease in ozone-related mortality (−30% as EU average). Due to aging and increasingly susceptible populations, the decrease in 2050 would be smaller, up to −24%. During summer months, ozone risks could combine with increasing temperatures, especially during the hottest periods and in densely populated urban areas. While the heat burden is currently of the same order of magnitude as ozone, due to increasing temperatures and decreasing ozone precursor emissions, heat-related mortality could be twice as large as ozone-related mortality in 2050.

## Introduction

The relationship between climate change, higher temperatures, and near-surface ozone formation and mortality is well established. Climate change is expected to increase global temperatures (IPCC 2013) and the probability of heat extremes (Christidis *et al* 2014, Seneviratne *et al* 2014); both have substantial effects on human health (Hajat and Kosatky 2010, Astrom *et al* 2011, Gasparrini *et al* 2015). Tropospheric ozone is a secondary pollutant, formed by the reactions of a mixture of nitrogen oxides and methane, carbon monoxide and non-methane volatile organic compounds from biogenic and anthropogenic sources. Biogenic emissions of ozone precursors are dependent on temperature, solar radiation and available moisture in air and soils (Andersson and Engardt 2010). The rate of formation of ozone in the troposphere is dependent on photolytically available sunlight (i.e. cloudiness, time of day, and latitude) and some of the involved reaction rates are temperature-dependent (Atkinson *et al* 2006). Mixing height, wind speed, and direction are also important meteorological factors. Studies have shown a dependency in near-surface ozone concentration on such meteorological factors, for example a positive correlation with temperature (Coates *et al* 2016). Therefore, changes to cloudiness, moisture, wind patterns, boundary layer height, and temperatures in the future could lead to changes in ozone concentrations, however the relevant processes are complex and advanced models are needed to understand the change. The impact of climate change on near-surface ozone in Europe has been studied extensively with such models, showing that there will likely be a climate penalty in central and southern Europe, i.e. increased ozone with climate change (Jacob and Winner 2009). Nevertheless, due to political and subsequent technological efforts, anthropogenic ozone precursor emissions have decreased since the 1990s and are expected to continue decreasing in the future–both in north America and Europe (Hidy and Blanchard 2015). For example, in the European ECLAIRE emissions (V4a) by Klimont *et al* (2013), the decrease in anthropogenic ozone precursor emissions is strong both for the 'current legislation' (CLE) and for the 'maximally technically feasible' (MTF) scenarios until 2050. The CLE describes enforcement of all current legislative measures until 2030, but no additional measures, and has smaller decreases in precursor emissions compared to the MTF. Projections of future near-surface ozone concentrations, based on such future emission scenarios, result in a strong decrease in future ozone concentrations in Europe (Markakis *et al* 2016, Watson *et al* 2016).

Past studies have estimated the future health effects of summertime ozone (Ebi and McGregor 2008, Sujaritpong *et al* 2014, Orru *et al* 2017) and high temperatures (Huang *et al* 2011, Sanderson *et al* 2017) globally, regionally, and locally, but very few have explored the long-term effects of ozone (Seltzer *et al* 2018), and ozone and temperatures simultaneously (Lee *et al* 2017). Moreover, there is limited knowledge about how other factors, such as decreases in ozone precursor emissions (Geels *et al* 2015, Karlsson *et al* 2017) and changes in susceptible populations (Arbuthnott *et al* 2016, Petkova *et al* 2017) might affect projected health burdens.

We project changes in ozone- and heat-related mortality in Europe and explore the individual and joint effects of climate, ozone precursor emissions, and demographic change.

## Methods

The methods for calculating European-wide (EU-27, Norway, Switzerland) near-surface temperature and ozone concentrations are described elsewhere (Lacressonnière *et al* 2016, Markakis *et al* 2016, Watson *et al* 2016). In summary, both climate and air pollution were modelled at a horizontal resolution of 0.44° × 0.44° (ca 50 km × 50 km) covering Europe (the full domain is the EURO-CORDEX domain, which is slightly larger than that which is shown in this analysis). For the calculation of temperature and other meteorological variables used as input to the air pollution dispersion model, the global climate model EC-EARTH was applied, downscaled with the Rossby Climate regional climate model RCA4 (Strandberg *et al* 2015) forced by the representative concentration pathway scenario RCP4.5 (Thomson *et al* 2011). The situation in 1991–2000 was compared with the future climate in 2046–2055 (centred on 2050). For the calculation of ozone concentrations, the Multi-scale Atmospheric Transport and Chemistry (MATCH) model (Robertson *et al* 1999, Andersson *et al* 2015) was used covering Europe, forced by the RCA4 climate, boundaries from LMDz-INCA global model (Hauglustaine *et al* 2004) for present (2005) and future (2050) and with anthropogenic air pollution precursor emissions of ECLIPSE v4a for present (year 2005) and future (year 2050, current legislation). The evolution is considered coherent with the future evolution of the RCP4.5 scenario at 2050 (Klimont *et al* 2013, Watson *et al* 2016). This scenario describes a strong decrease in anthropogenic ozone precursor emissions in Europe from 2005 until 2050, e.g. NOx and NMVOCs are reduced by 43% and 45%, respectively, (for an illustration, see e.g. figure 2 in Watson *et al* 2016). The future period was chosen to coincide with the period when a 2° climate change occurs (compared to the pre-industrial climate).

MATCH has been used extensively to study the connections between climate change and air quality in Europe (e.g. Engardt et al 2009, Andersson and Engardt 2010, Watson *et al* 2016). The photochemistry of the MATCH model considers time of day, latitude, and cloudiness, where the photochemical reaction rates were adjusted for cloud cover. Biogenic emissions of isoprene were modelled online, dependent on temperature and solar radiation, while soil moisture was not taken into account for the online emissions. This is likely to cause an overestimation in the change to the future of biogenic emissions, especially in southern Europe. The dry deposition is dependent on boundary layer meteorology, as well as on parameters affecting vegetation uptake, such as soil and air moisture, temperature, and solar radiation. This was previously shown to be important for modelling future near-surface ozone in southern Europe, particularly in the Iberian Peninsula (Andersson and Engardt 2010). Natural NOx emissions from lightning were not included, while wildfires were included from the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP) database (Lamarque *et al* 2010).

Gridded population data for Europe in 2010 and 2050 were obtained from the Integrated Assessment of Health Risks of Environmental Stressors in Europe (INTARESE) and Health and Environment Integrated Methodology and Toolbox for Scenario Development (HEIMSTA), where the current and future gridded population data sets were constructed (Kuhn *et al* 2011). Based on these, the population-weighted ozone exposure in each country was calculated (see methods and equations in more detail in supplementary material and (Orru *et al* 2009, Orru *et al* 2013)). Data and projections regarding high temperatures among the total population and the population above 65 years of age were collected on a spatial scale of a similar resolution as the climate data for 2000 and 2050 (Kuhn *et al* 2011). Each population data point was assigned to the closest climate data grid square central point (see methods in more detail in Åström *et al* 2017).

The average baseline all-cause mortality rates in 2010 were attained from WHO's European Health for All Database (WHO 2019) and applied to all grids within each country. Each driver (climate, ozone precursor emissions, population) was projected individually, keeping other factors constant, to explore the effects of the individual drivers (e.g. ozone or temperature) on future mortality change. To describe the ozone effects associated with long-term and short-term exposures, the exposure–response functions (relationship between exposure to pollution as a cause and specific health outcomes as a response) from earlier epidemiological studies were applied. For the calculation of long-term effects, the Hazard Ratio, HR = 1.014 (95% CI 1.007–1.028) per 10 $\mu gm^{-3}$ increase in annual mean of daily 8 h maximum from Turner *et al* (2016) was used; this study quantified the long-term effects of ozone. For short-term exposure effects, the Relative Risk, RR = 1.0031 (95% CI 1.0017, 1.0052) per increase in the 8 h ozone max concentration by 10 $\mu gm^{-3}$ from Gryparis *et al* (2004) was applied; this study quantified short-term ozone effects.

The numbers of premature mortalities were calculated based on health impact assessment principles and equations described in more detail in (Orru *et al* 2013). In the health impact assessment, usual cut-off values were applied, representing concentrations close to natural background not associated with an increase in risk (Lehtomäki *et al* 2018). In the current study, the 25 ppb cut-off value was applied to the calculations for effects of long-term ozone exposure, and SOMO10, SOMO25 and SOMO35 (sum of means over 10, 25 and 35 ppb) values were used for the short-term effect calculations.

To measure harmful exposures from high temperatures, we used the framework from a European multi-city study within the Public Health Adaptation Strategies to Extreme Weather Events (PHASE) project. The estimated risk increase in that study was based on the difference in mortality between the 75th and the 99th percentile of summer daily mean temperatures (de'Donato *et al* 2015). We used a 22.9% increase in mortality associated with a temperature increase from the 75th to the 99th percentile (exposure–response function (ERF)) averaged over all cities in the PHASE study.

In our analyses, the 75th percentile of mean temperatures (temperatures where the heat effects start) were calculated for each of the cells in the gridded 50 × 50 km climate data and matched with the population data. For each grid cell, we calculated the projected total annual average heat exposure over the two time periods. The aggregated extra mortality attributable to heat was calculated based on current and future temperature and ERF. Future mortality was assessed using both present day and future population size.

## Results

Current mean annual near-surface ozone concentrations vary in Europe from a high of 105.8 $\mu gm^{-3}$ in Southern Europe to a low of 52.7 $\mu gm^{-3}$ in Northern Europe (figure 1). A similar South–North trend appears for SOMO10,25,35 values (figures S1–S3 are available in the supplementary material online at stacks.iop.org/ERL/14/074013/mmedia). Future ozone concentrations are projected to increase due to climate change alone in Southern and Central Europe and decrease in Northern Europe. Taking into consideration declining precursor emissions, near-surface ozone levels are expected to be somewhat smaller in the future compared to their current levels. The effects of climate change are project to be much higher for SOMO35 values than for SOMO25 or SOMO10 values (figures S1–S3). This suggests that climate change could have a bigger effect on the more extreme values of ozone that are largely associated with the increase of higher temperatures in Europe and somewhat connected to increased isoprene emissions and soil moisture, which regulates dry deposition (Andersson and Engardt 2010). The largest increase of harmful temperatures is projected in Southern Europe, while Eastern Europe has the smallest projected increase. The increase ranges from about 25% in Lithuania to more than a 100% increase in Malta and Cyprus.

Current exposure to near-surface ozone in Europe is expected to cause around 56 000 premature deaths in Europe annually (table 1), including a proportion of the estimated 26 000 deaths per year expected due to short-term exposures (assuming a threshold at 25 ppb) (table S1). With climate change, the effects of long-term ozone exposure are expected to increase in the Central-European countries of Germany, France,

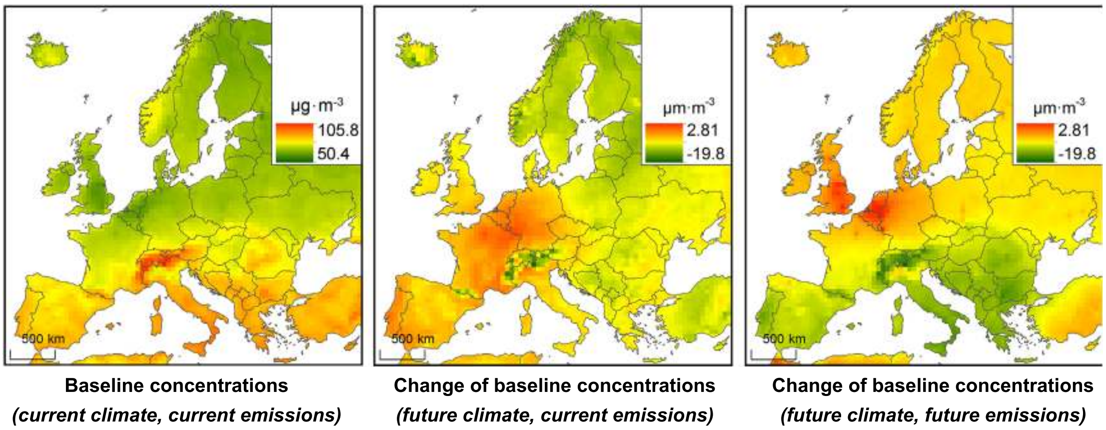


**Figure 1.** Current mean annual daily near-surface ozone concentrations ($\mu g \cdot m^{-3}$) (left figure) and change of current mean under current (1991–2000) and future (2046–2055) climate and emission scenarios.

**Table 1.** Current (2010) and future (2050) annual premature deaths due to long-term exposure to near-surface ozone and heat in the EU-27 Union countries, Norway, and Switzerland.

| | Near-surface ozone | | | | | Heat | | |
|---|---|---|---|---|---|---|---|---|
| | Current situation | Future climate[a] | Future population[a] | Future emissions[a] | Future combined | Current climate | Future climate | Future climate and population |
| Austria | 1061 | 1039 | 1133 | 722 | 742 | 886 | 1313 | 1333 |
| Belgium | 663 | 709 | 726 | 594 | 677 | 1031 | 1489 | 1599 |
| Bulgaria | 1861 | 1812 | 1408 | 1169 | 854 | 1342 | 2329 | 1676 |
| Cyprus | 119 | 115 | 179 | 99 | 147 | 96 | 207 | 277 |
| Czech Republic | 1315 | 1311 | 1347 | 905 | 904 | 1444 | 2017 | 1990 |
| Denmark | 481 | 463 | 493 | 354 | 349 | 574 | 915 | 926 |
| Estonia | 150 | 138 | 144 | 99 | 88 | 181 | 265 | 245 |
| Finland | 387 | 356 | 405 | 266 | 257 | 568 | 905 | 922 |
| France | 6130 | 6321 | 7021 | 4180 | 4822 | 5411 | 8698 | 9439 |
| Germany | 7020 | 7273 | 6326 | 5381 | 4826 | 8126 | 11 951 | 10 321 |
| Greece | 1876 | 1844 | 1927 | 1260 | 1273 | 1252 | 2493 | 2443 |
| Hungary | 1672 | 1623 | 1567 | 1026 | 922 | 1607 | 2311 | 2069 |
| Ireland | 362 | 354 | 567 | 269 | 414 | 516 | 882 | 1208 |
| Italy | 8349 | 8297 | 8135 | 5701 | 5442 | 6007 | 10 815 | 10 282 |
| Latvia | 280 | 256 | 248 | 180 | 143 | 348 | 450 | 373 |
| Lithuania | 394 | 357 | 339 | 252 | 194 | 496 | 629 | 498 |
| Luxembourg | 29 | 32 | 44 | 27 | 43 | 51 | 76 | 114 |
| Malta | 79 | 78 | 92 | 55 | 64 | 50 | 113 | 117 |
| Netherlands | 1032 | 1083 | 1106 | 961 | 1048 | 1499 | 2306 | 2409 |
| Norway | 382 | 359 | 495 | 281 | 345 | 509 | 839 | 1027 |
| Poland | 4171 | 3945 | 4075 | 2805 | 2561 | 5046 | 6665 | 5615 |
| Portugal | 1595 | 1631 | 1607 | 1058 | 1072 | 1113 | 2031 | 1903 |
| Romania | 4121 | 3990 | 3767 | 2568 | 2276 | 3681 | 5753 | 4691 |
| Slovakia | 863 | 836 | 902 | 559 | 561 | 870 | 1239 | 1127 |
| Slovenia | 319 | 315 | 325 | 212 | 210 | 234 | 353 | 343 |
| Spain | 5428 | 5456 | 6378 | 3717 | 4367 | 4446 | 8294 | 9395 |
| Sweden | 680 | 639 | 790 | 481 | 525 | 911 | 1503 | 1710 |
| Switzerland | 904 | 894 | 1020 | 627 | 685 | 689 | 1111 | 1245 |
| United Kingdom | 3877 | 3852 | 4683 | 3382 | 4056 | 6000 | 9447 | 11 041 |
| Total EU-27 + 2 | **55 597** | **55 380** | **57 250** | **39 192** | **39 867** | **54 988** | **87 398** | **86 337** |

[a] Other changing factors kept constant.

Belgium, and Luxembourg, and decrease in most Nordic and Baltic countries (table 1). Similar trends occur for short-term exposure effects, depending on the SOMO value (table S2). Assuming effects only on higher ozone values (SOMO35), the total EU-wide climate change effects could be around 4%, but in some countries such as Belgium and Luxembourg, the increase would be up to 25% and 31%, respectively.

Increases in the total and over-65 population would affect future ozone-related mortality (e.g. Luxembourg, Ireland, and Cyprus) and/or increase of share of susceptible individuals (especially in Ireland, Cyprus, and Malta) (table 1). These effects could be larger than the individual effect of climate change on ozone concentrations. With a scenario assuming a medium population growth rate, the increase in the ozone health burden could be up to 57% in countries such as Ireland, Cyprus, and Malta. The total for Europe is projected to be a 3% increase. Population decreases in some countries would reduce the ozone health burden by more than around 10% (Latvia and Lithuania) or 24% in Bulgaria.

Much larger decreases (−30% EU-wide) in ozone-related mortality are projected due to reductions in ozone precursor emissions (table 1). The overall decrease could vary from −37% in Bulgaria to −7% in Netherlands and Luxembourg. In general, larger decreases are expected in Eastern-European countries and smaller decreases in Central-European countries. Summing all different factors together, a −28% decrease in ozone-related mortality could be expected EU-wide by 2050 (table 1).

High ambient temperatures currently have a very similar magnitude of health burden relating to exposure to near-surface ozone (1% smaller). There are significant differences between countries: Belgium, Finland, Germany, Ireland, Luxembourg, the Netherlands, Sweden, and the UK have significantly higher burdens, and Bulgaria, Cyprus, Greece, Italy, Portal, and Spain have lower health burdens compared with that of ozone. With climate change and increased temperatures, heat-related mortality is expected to increase by 59% EU-wide by 2050. The increase will be largest in already warm countries as Cyprus, Greece, Italy, Portugal, and Spain, with smaller increases expected in Baltic and Eastern-European countries like Latvia, Lithuania, Poland and the Czech Republic (table 1).

## Discussion

The health burdens associated with exposure to near-surface ozone levels were projected to change in the future, with increases due to climate change and the size of susceptible populations in Europe, and decreases due declining concentrations of ozone precursor emissions; the net result was projected to be a decrease in the total health burden in 2050. Increasing temperatures as a result of climate change were projected to double heat-related mortality, making heat a larger health threat in the future.

This is the second large-scale study where these two important health factors were combined in the same population using a similar climate model and scenarios. Lee *et al* (2017) projected smaller future heat-related mortality increases in Korean cities, while the effects of climate change on ozone-related mortality remained the same order of magnitude, slightly increasing or decreasing depending on the city and RCP used (Lee *et al* 2017).

The average heat–mortality relationship from the PHASE study was used in our analyses because many countries did not have a country-specific exposure–response function calculated in that study. Therefore, using the average European function was the best way to generate estimates for all countries.

We focused on RCP4.5, a rather optimistic scenario compared to RCP8.5. Even so, under RCP4.5 around a 2 °C global average temperature increase can be expected by 2050 (IPCC 2013), which is the threshold increase under the Paris Agreement. We project up to a 59% increase in heat-related mortality in 2050 compared to 2000 if the 2 °C threshold is accomplished, a significant and concerning increase.

Compared with earlier large-scale studies in Europe (Orru *et al* 2013, Patz *et al* 2014, Geels *et al* 2015, Silva *et al* 2017), we found the impact of climate change on ozone-related mortality was somewhat smaller. One difference in this analysis is that we included the health impacts of ozone exposure over the long term, while the earlier estimates were based on only short-term exposure, which might have underestimated the total near-surface ozone burden in Europe but overestimated the change. If we compare the climate change-related effects using only short-term exposures as SOMO35, the effects of climate are of the same magnitude as reported previously (Orru *et al* 2013). This indicates that climate could have a larger effect on very high short-term concentrations of near-surface ozone. Compared to the recent study by Seltzer *et al* (2018), we found somewhat larger effects of near-surface ozone for Europe, as our estimates are based on all-cause mortality.

As shown in sensitivity analysis in earlier studies (Malley *et al* 2017), ozone health effects are highly sensitive to the threshold levels assumed: e.g. 10, 25, 27.7, 31.1, 33.3, 35, 41.9 ppb. As the epidemiological studies quantified health effects at lower concentrations (Bell *et al* 2006), we used a 25 ppb threshold as the main scenario. We applied only one climate model and one RCP scenario, to show the sensitivity of the projections to other important variables. The results will vary depending on the climate model and greenhouse gas emission scenarios used, both for temperature (Åström *et al* 2017) and for ozone (Post *et al* 2012). A key difference with earlier studies is that we used a different greenhouse gas emission scenario to project the impact of climate change on ozone-related mortality. In our earlier analysis (Orru *et al* 2013), we applied the A2 and A1B greenhouse gas emission scenarios using the global climate models ECHAM4 and HadCM3, respectively, and the MATCH version was different. A2 is more pessimistic in terms of greenhouse gas emissions than RCP4.5 and HadCM3 has a stronger climate sensitivity. Geels *et al* (2015) used the same greenhouse gas emission scenario used in this study, but used the global climate model ECHAM5 instead of EC-EARTH.

In this study, we used a relatively coarse resolution (0.44° × 0.44°) that does not take into account a decrease of ozone by the titration effect of nitrogen oxide (NO) in city centres. This means that ozone exposure was likely overestimated close to where high emissions occur (e.g. Markakis *et al* 2016), but underestimated in suburban areas in the outskirts of city centres where local emissions could increase near-surface ozone. Measures to reduce NO emissions locally may have the counter-benefit of increasing ozone exposure. This also means that our coarse resolution may result in overestimation of the change in population exposure due to emission change in the future. It is currently not technically feasible to describe ozone exposure at a very high resolution to take this effect into account across all of Europe. $NO_X$ emissions do also affect fine particle ($PM_{2.5}$) levels through formation of ammonium nitrate particles that has a substantial effect on public health, but this effect is not taken into account in this study. Further research is needed in those areas.

In our assessment, we applied population change by 2050, but did not assess the sensitivity of changes in mortality rates in 2050 as was done by Sun *et al* (2015). Because mortality rates have been decreasing in Europe, this could have been another reason why the projected health effects on SOMO35 levels were smaller than in earlier publications (Orru *et al* 2013). It is possible that population growth could be faster, which would make future health burdens even larger (table S3). Also, we did not consider the possible effects of future adaptation to warmer temperatures by the at-risk population because the modelling of adaptation to warmer temperatures is currently arbitrary and simplistic (Sanderson *et al* 2017). In this analysis, we only projected the increase of heat-related mortality, and we did not take into account that there may be somewhat smaller decreases of cold-related mortality in some countries with climate change (Gasparrini *et al* 2017).

In our analyses, some countries currently have higher ozone-related health burdens compared to heat effects and vice versa (e.g. Spain with higher ozone *versus* Sweden with higher heat-related health burdens). On the one hand, this might be driven by the higher proportion of respiratory mortality in the total cardiopulmonary burden in 2010, indicating the high sensitivity of baseline mortality data. On the other hand, there are differences in heat sensitivity, with people in colder climates tending to be more sensitive to high temperatures than people in warmer climates (Medina-Ramon and Schwartz 2007).

The emission scenario ECLIPSE v4a (current legislation; (Klimont *et al* 2013)) features a strong decrease in anthropogenic ozone precursor emissions from present to future, resulting in significantly lower concentrations of anthropogenic ozone (Markakis *et al* 2016, Watson *et al* 2016) that in turn results in reduced ozone-related health effects. Similar declines in ozone future precursor emissions in Europe were projected (Doherty *et al* 2017). However, there are inherent uncertainties related to future greenhouse gas emissions and the resulting climate change that could impact projected air pollution-related health impacts (Orru *et al* 2017). The decreases in future emissions could be lower than expected based on different emission inventory estimates and earlier projections for $NO_X$, VOC and $NH_3$ (Amann *et al* 2015). $NO_2$ levels have stabilised in recent years in several monitoring sites in Europe (Guerreiro *et al* 2014). Low percentiles of ozone in European and USA cities are increasing, while peak values are decreasing (Paoletti *et al* 2014); similar trends have been confirmed by modelling (Andersson *et al* 2017).

Ozone precursors were projected to increase in Asia (Lin *et al* 2017) and somewhat in the US (Wu *et al* 2008) over the same time period. How this global increase would increase background near-surface ozone levels is not yet clear. Also, under a higher greenhouse gas emission scenario, such as RCP8.5 with high global methane concentrations, the transboundary transport of ozone could be accelerated and cancel the projected benefits of European emission reductions on air quality (Fortems-Cheiney *et al* 2017). Fulfilling the Paris Agreement aims is essential to reduce emissions and protect health. We also should clearly communicate the future negative health burden possible under the Paris Agreement. Certainly we could expect increases in heat-related mortality in Europe that would require even better health policies and programs to protect increasing susceptible and aging populations.

## Conclusions

Climate and emission changes will substantially affect ozone and heat-related mortality and the ratio between them in the middle of this century in Europe. Heat will become a more important health concern in the future, emphasising the importance of increasing resilience to a warmer world.

Although near-surface ozone-related mortality is projected to be smaller in the future (mainly due to precursors emission decrease), the reduction is not as large as it could be because of climate change and an increasingly susceptible population. Therefore, it is essential to continue to decrease ozone precursor emissions.

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## Author contributions

HO conceived the study, CA modelled the near-surface ozone and temperature; HO, KE, and BF designed the research; TT performed the GIS analyses and made maps; HO and CÅ made the health impact calculations; and all authors wrote the paper.

## Conflict of interest

The authors declare no conflict of interest.

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