GeoHealth

RESEARCH ARTICLE

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Key Points:

- Strong mitigation of aerosols and ozone precursors leads to large future benefits to the air pollution health burden, particularly over Asia
- Future climate change can offset the health benefits of a reduced air pollution health burden from emissions mitigation over Europe and East Asia
- It is important to consider future chemical environments when designing measures to maximize benefits to climate, air quality, and health

Supporting Information:

Supporting Information may be found in the online version of this article.

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The Air Pollution Human Health Burden in Different Future Scenarios That Involve the Mitigation of Near-Term Climate Forcers, Climate and Land-Use

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Abstract

Elevated surface concentrations of ozone and fine particulate matter ($PM_{2.5}$) can lead to poor air quality and detrimental impacts on human health. These pollutants are also termed Near-Term Climate Forcers (NTCFs) as they can also influence the Earth's radiative balance on timescales shorter than long-lived greenhouse gases. Here we use the Earth system model, UKESM1, to simulate the change in surface ozone and $PM_{2.5}$ concentrations from different NTCF mitigation scenarios, conducted as part of the Aerosol and Chemistry Model Intercomparison Project (AerChemMIP). These are then combined with relative risk estimates and projected changes in population demographics, to estimate the mortality burden attributable to long-term exposure to ambient air pollution. Scenarios that involve the strong mitigation of air pollutant emissions yield large future benefits to human health (25%), particularly across Asia for black carbon (7%), when compared to the future reference pathway. However, if anthropogenic emissions follow the reference pathway, then impacts to human health worsen over South Asia in the short term (11%) and across Africa (20%) in the longer term. Future climate change impacts on air pollutants can offset some of the health benefits achieved by emission mitigation measures over Europe for $PM_{2.5}$ and East Asia for ozone. In addition, differences in the future chemical environment over regions are important considerations for mitigation measures to achieve the largest benefit to human health. Future policy measures to mitigate climate warming need to also consider the impact on air quality and human health across different regions to achieve the maximum co-benefits.

Plain Language Summary

Ground level ozone (O_3) and fine particulate matter ($PM_{2.5}$) are two major air pollutants that are associated with adverse effects to human health. In addition, changes in their atmospheric concentrations can also influence the rate of climate change on a timeframe shorter than that for long-lived greenhouse gases. In this study we use a global Earth system model to simulate the change in concentrations of surface O_3 and $PM_{2.5}$ across numerous future mitigation scenarios, which are then used to quantify the impact on the air pollution health burden. A large reduction in the air pollutant health burden of the population, particularly across Asia, is calculated in scenarios that have large reductions in air pollutant sources. However, impacts on health can increase across large parts of Africa in a scenario where emissions of air pollutants are not reduced. Future climate warming increases the exposure to air pollutants across regions such as Europe and East Asia, with a detrimental impact on human health. Measures to limit future climate warming and improve regional air pollutant health burdens are interconnected and important to consider together when designing future policies.

1. Introduction

It is well established that exposure to elevated concentrations of air pollutants in the lowest layers of the atmosphere can lead to a number of detrimental health effects including respiratory and cardiovascular diseases, lung cancer, and premature mortality (Chen & Hoek, 2020; Jerrett et al., 2009). In fact, negative human health consequences from long-term exposure to air pollutants is currently the largest global environmental risk factor (Murray et al., 2020). Ambient fine particulate matter with an aerodynamic diameter of less than 2.5 µm ($PM_{2.5}$) and ozone (O_3) are two important air pollutants in the lower atmosphere leading to detrimental impacts on human health. In addition, these pollutants are also termed near-term climate forcers (NTCFs) as they can influence the

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Earth's radiative balance on climate timescales that are much shorter than greenhouse gases due to their shorter residence time in the atmosphere. Future policy measures to mitigate greenhouse gas emissions to address climate change will also involve changes to NTCF emissions since they share the same emission sources. Therefore, it is important to understand the future human health implications from changes in NTCFs under different climate pathways, especially in the context of mitigation measures to limit future climate warming.

Exposure to present-day (2015–2019) ambient $PM_{2.5}$ concentrations is calculated in the Global Burden of Disease (GBD) study to result in approximately 4 million global mortalities annually (Cohen et al., 2017; Murray et al., 2020; WHO, 2016). However, a study by Burnett et al. (2018), using the Global Exposure Mortality Model (GEMM), calculates this number to be approximately 9 million global mortalities per year. For exposure to present-day (2019) ambient surface O_3 concentrations, the GBD study estimates this results in approximately 365,000 global mortalities annually from chronic obstructive pulmonary disease (COPD) (Murray et al., 2020). Including the health effects from all chronic respiratory diseases, Malashock et al. (2022a) revised this estimate up slightly to ∼423,000 global mortalities per year. However, using updated O_3 exposure-response functions from M. C. Turner et al. (2016), global mortalities due to all respiratory diseases from exposure to O_3 in the 2010s was estimated to be ∼1.1 million (Chowdhury et al., 2020; Malley et al., 2017). Overall, the long-term impacts on human health from exposure to fine particles is considered to be much larger than that from O_3.

In recent decades, policy interventions to mitigate air pollutant emissions across both Europe and North America have resulted in benefits to human health associated with exposure to $PM_{2.5}$ across these continents (Butt et al., 2017; Turnock et al., 2016). More recently, policy action to decrease the concentrations of air pollutants across China, namely $PM_{2.5}$, has reduced the burden on human health (Silver et al., 2020; Wang et al., 2022). Despite these recent actions, concentrations of air pollutants continue to increase across many parts of the world, exposing the population to levels that are deemed detrimental to human health and above the World Health Organization's (WHO) Air Quality Guideline Values (AQGVs) (Shaddick et al., 2020). This is particularly the case for global ozone-attributable mortality which has increased by 46% from 2000 to 2019 (Malashock et al., 2022b). Any future climate policy measures should therefore also seek to reduce the global health burden from exposure to air pollutants at the same time as mitigating climate change.

The emphasis of climate policies to reduce the impact of climate change has tended to focus on decreasing the emissions of long-lived greenhouse gases, mainly carbon dioxide, and sometimes with little consideration for sources of air pollutants and NTCFs. However, because changes in climate, air quality and the human health burden are all interconnected, climate policies leading to a reduced rate of future warming can also have a co-benefit of improved air quality and human health (Allen et al., 2020; Hamilton et al., 2021; Shindell et al., 2018; Turnock et al., 2019; West et al., 2013). It should also be noted that future socio-demographic changes (e.g., population aging and baseline mortality rates) can also have a large influence on the future health burden (Conibear, Butt, Knote, Spracklen, & Arnold, 2018; Conibear et al., 2022; Rafaj et al., 2021; Yang et al., 2023). Previous studies have quantified the human health burden from exposure to air pollutants in different future climate scenarios. Silva et al. (2016) used a multi-model ensemble from the Atmospheric Chemistry and Climate model intercomparison project (MIP) (ACCMIP, Lamarque et al., 2013) to show that the global human health burden from exposure to O_3 and $PM_{2.5}$ tended to reduce across all future scenarios due to pollutant concentrations being reduced. However, the health burden from exposure to O_3 increased in the one future scenario that increased surface O_3 concentrations due to higher global CH_4 concentrations and a larger climate change signal. This study also highlighted the importance of future changes in population and baseline mortality to the health burden calculations. However, the study used the Representative Concentration Pathway scenarios, as part of the 5th Coupled Model Intercomparison Project (CMIP5), which failed to adequately account for the range of future air pollutant emission trajectories (Rao et al., 2017). Yang et al. (2023) used a single model to simulate pollution concentrations and calculate the air pollution health burden in five different future scenarios used in the 6th Coupled Model Intercomparison Project (CMIP6). The results showed the air pollution health burden varies by a factor of 2 across the different future scenarios with the lowest burden in scenarios that include stringent policies for both air pollution and climate. Considering only the impact from climate change resulted in the future air pollution (both O_3 and $PM_{2.5}$) mortality burden increasing by the end of the 21st Century across most regions (Silva et al., 2017). At a regional level, the future $PM_{2.5}$ health burden is projected to increase across India in the early part of the 21st Century before reducing in all future climate change scenarios, except in the high emission and temperature scenario of CMIP5 (Chowdhury et al., 2018). Over China, exposure to $PM_{2.5}$ is expected to decline in all future scenarios, although changing population demographics means that this does not always necessarily

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Table 1
Sensitivity Scenarios Conducted by UKESM1 Detailing the Configurations Used for Near-Term Climate Forcers, Land-Use and Climate

Experiment	Anthropogenic air pollutant precursors			Land-use	Climate
	Aerosols	Ozone (non-CH_4)	Methane		
ssp370SST	Reference	Reference	Reference	Reference	Reference
pdSST	Reference	Reference	Reference	Reference	2005–2014 climatology for SST and SI fields, DMS and Chlorophyll concentrations and CO_2 concentrations
pdEmis (non-AerChemMIP experiment)	Fixed at 2014 values	Fixed at 2014 values	Fixed at 2014 values	Reference	Reference
ssp126LU	Reference	Reference	Reference	ssp126	Reference
lowAer	Clean	Reference	Reference	Reference	Reference
lowBC	Clean (only for BC)	Reference	Reference	Reference	Reference
lowO3	Reference	Clean	Reference	Reference	Reference
lowCH4	Reference	Reference	Clean	Reference	Reference
lowNTCF	Clean	Clean	Reference	Reference	Reference
lowNTCFCH4	Clean	Clean	Clean	Reference	Reference

Note. Reference = ssp370 and Clean = ssp126.

translate into an overall health benefit (Conibear et al., 2022; Shim et al., 2021; Wang et al., 2022; Xu et al., 2022). Significantly lower air pollution ($PM_{2.5}$) mortality estimates of ~800,000 per year by 2100 are estimated to occur across Africa in a future scenario that involves reduced warming levels and air pollutant emission reductions, compared to a higher warming scenario with weaker emission mitigation resulting in ~1.3 million per year by 2100 (Shindell et al., 2022).

Turnock et al. (2022) analyzed both the air quality and climate impacts from changes in NTCFs in a wide range of future mitigation pathways, conducted as part of the Aerosol and Chemistry MIP (AerChemMIP), an endorsed MIP of CMIP6. Within AerChemMIP, the future mitigation scenarios consider different pathways of both strong (working toward implementing best available technology for maximum feasible reductions) and weak (delays to implementing current control legislation and any future reductions) pollution control measures, which impact the emissions of NTCFs. Large co-benefits to both air quality and climate were identified in scenarios which involved strong future mitigation of aerosols, O_3 precursors (CO, NO_x, and volatile organic compounds [VOCs]) and methane, with penalties identified for inaction. Individual mitigation scenarios for NTCFs showed non-linear results when compared to combined mitigation. Scenarios considering only the impact from changes in climate and land-use highlighted important differences at a regional level. Here we use the same scenarios as in Turnock et al. (2022) to calculate the air pollution health burden resulting from changes in surface O_3 and $PM_{2.5}$ concentrations in a wide range of future scenarios simulated by the United Kingdom Earth System Model (UKESM1, Sellar et al., 2019), as part of AerChemMIP. We quantify the change in the air pollution health burden for scenarios that include the mitigation of different NTCFs, both individually and in combination, as well as isolating the impacts from transient changes in climate, emissions, and land-use.

2. Materials and Methods

2.1. Model Simulations and Future Scenarios

A detailed explanation of the model setup, emission scenarios and simulations performed for this study can be found in the companion paper (Turnock et al., 2022), with a brief summary also presented here. We use the fully coupled Earth system model, UKESM1, which contains an interactive stratosphere-troposphere chemistry and aerosol scheme coupled to the physical atmosphere ocean climate model, along with other relevant Earth system components such as a terrestrial carbon and nitrogen cycle coupled to a dynamical vegetation model (Sellar et al., 2019, 2020). Within this model, changes in climate and land-use can feed back onto atmospheric composition by altering natural emissions (e.g., biogenic VOCs, dust, sea salt) or physiochemical processes (e.g., reaction rates, deposition) (Archibald et al., 2020; Mulcahy et al., 2020). It is therefore an appropriate model tool with which to study future changes in air pollutants under different climate and emission mitigation scenarios.

The scenarios used in this study were all designed for use in CMIP6 and AerChemMIP (Collins et al., 2017). The Shared Socio-economic Pathway associated with ssp370 ("regional rivalry" with high challenges to mitigation and adaption and weak air pollution controls; Rao et al., 2017; Riahi et al., 2017) was selected by AerChemMIP as the future reference scenario to allow for the largest response to be generated. Results from the "atmosphere only" simulation labeled ssp370SST are used as the reference in this study, which takes values relevant to the ocean and land surface from the fully coupled companion experiment. Using the ssp370SST simulation allows for multiple sensitivity scenarios to be considered on top of this reference, which are detailed in Table 1. Sensitivity scenarios either involve the individual (lowBC, lowAer, lowO3, and lowCH4) or combined (lowNTCF and lowNTCFCH4) mitigation of NTCFs, a reduction of approximately 50%, toward a more sustainable future pathway of SSP1 using maximum technically feasible pollution controls (Collins et al., 2017; Gidden et al., 2019). Scenarios that reduce emissions of compounds individually highlight the effects of each type of control, but do not represent realistic emission control options, which would likely affect emissions of many species simultaneously. Additional scenarios have also been undertaken to isolate any impact from solely future changes in climate (pdSST), anthropogenic emissions (pdEmis), and land-use (ssp126LU), which can increase natural sources of NTCFs. Future details of the emission changes in these scenarios can be found in Turnock et al. (2022). All the scenarios listed in Table 1 have been conducted in UKESM1 over the period 2015–2100. The changes in air pollutant concentrations in each scenario are calculated relative to the reference scenario ssp370, apart from for climate change and emissions which are calculated as the difference between ssp370 and pdSST, pdEmis, respectively, which are then translated into impacts on human health.

Hourly mean output of surface O_3 and monthly mean output of $PM_{2.5}$ relevant diagnostics (mmrbc, mmrso4, mmroa, mmrss, and mmrdust) were obtained from UKESM1 for each of the sensitivity scenarios from a single model realization. Data for $PM_{2.5}$ diagnostics were obtained from each year of the single realization of the histSST experiment for a present-day time period (2005–2014) and for each year of the whole time period of each future simulation (2015–2099). For O_3, 10-year time periods were obtained for the present day (2005–2014) and two future time periods (2045–2054 and 2090–2099) due to the data volumes associated with hourly data. An approximate method was used to calculate $PM_{2.5}$ concentrations in these experiments, using the total aerosol mass of black carbon (BC), sulfate (SO_4), and organic aerosol, as well as 25% of the total sea salt mass and 10% of the total dust mass, to be consistent with other recent AerChemMIP studies (Allen et al., 2020, 2021; Turnock et al., 2020, 2022). Currently, there is no representation of nitrate aerosols within UKESM1, so this has been excluded from the $PM_{2.5}$ calculations and will likely result in an underestimation of between 0 and 5 μg m^{-3} in the overall simulated change in $PM_{2.5}$ concentrations in each scenario (A. C. Jones et al., 2021). For each scenario, we have calculated relevant air pollution metrics to use in the calculation of the impact on human health. For $PM_{2.5}$, annual mean values have been calculated and averaged for 10-year time periods in the future. Hourly mean surface O_3 values are first converted into the daily maximum of 8 hr running mean values (MDA8) and then a 6-month running mean is calculated for these values (6mMDA8). Finally, the annual maximum of these values within each year is calculated to represent the seasonal maximum daily exposure value, consistent with the metric used in the WHO air quality guidelines (https://apps.who.int/iris/handle/10665/345329). Each of these health relevant metrics can be compared to their relevant WHO AQGV (5 for $PM_{2.5}$ and 60 μg m^{-3} for O_3) and used in the assessment of long-term impacts on human health.

UKESM1 is a global model with a horizontal resolution of 1.875° × 1.25° or ∼140 km, meaning that it provides global changes in air pollutant concentrations that are relatively coarse when assessing the impact on human health from these concentrations. In addition, global composition climate models like UKESM1 have previously been shown to underestimate present day surface $PM_{2.5}$ concentrations and overestimate surface O_3 concentrations (Archibald et al., 2020; Mulcahy et al., 2020; Turnock et al., 2020). To alleviate some of these limitations, the present-day mean (2005–2014) surface O_3 and $PM_{2.5}$ concentrations from UKESM1 have first been corrected using observational data products generated at a finer spatial resolution of 0.1° × 0.1° (Delang et al., 2021; van Donkelaar et al., 2021). The corrected data is then re-gridded to match the horizontal resolution of the population data (0.125°) to create population-weighted mean values. This then provides a new present-day baseline of air pollutant concentrations, which are derived from observations as far as possible to eliminate some of these known biases in surface concentrations in a similar way to other recent air pollution health assessments (Chowdhury et al., 2020; Conibear et al., 2022; Shaddick et al., 2020), and makes the present day exposure values suitable for use in the calculation of the health response. Future changes in concentrations simulated by UKESM1 in each of the scenarios are then applied on top of this corrected baseline (see Text S1 in Supporting Information S1). Mortality is estimated in each grid cell at the 0.125° resolution of the population data.

2.2. Health Impact Assessment

The methodology for our air pollution health impact assessment follows that of Conibear et al. (2022). The impact on human health, in terms of premature adult (>25 years) mortality, from long-term exposure to $PM_{2.5}$ concentrations was calculated by using the global exposure mortality model (GEMM, Burnett et al., 2018). The GEMM uses relative risks based on long-term exposure to $PM_{2.5}$ concentrations in different age groups (see Text S2 in Supporting Information S1 for further details). The health outcome used in GEMM associated with $PM_{2.5}$ exposure was non-accidental mortality (non-communicable disease [NCD] plus lower respiratory infections [LRI]). We used the GEMM NCD + LRI with parameters that included the China cohort (Burnett et al., 2018), and with age-specific modifiers for adults over 25 years of age in 5-year intervals, which results in different health effects in each age group. The long-term $PM_{2.5}$ exposure values used with GEMM NCD + LRI were calculated as changes in the population-weighted 10-year mean values simulated in each scenario by UKESM1 applied on top of the corrected present-day baseline values (2005–2014) of UKESM1 simulation data. In comparison to other available exposure response functions for example, Integrated Exposure Response model or MRBRT used in GBD studies (Murray et al., 2020), the GEMM has been shown to estimate a larger present-day mortality burden from exposure to $PM_{2.5}$ concentrations. This is due to the use of higher hazard ratios derived from cohort studies that only consider outdoor air pollution (Burnett et al., 2022), although all methods have underlying assumptions and uncertainties associated with them (Pozzer et al., 2023). Yang et al. (2023) showed that using GEMM (for five specific causes of death) and IER led to comparable future cumulative global $PM_{2.5}$-related deaths in different SSPs. The GEMM is considered an appropriate method as it is based only on cohort studies of exposure to ambient air pollutant concentrations and has been used in many recent publications to provide an assessment of the future air pollution health burden (Conibear et al., 2022; Shindell et al., 2022; Wang et al., 2022; Yang et al., 2023). We use the GEMM here since this study is not focussed on the assessment of different health response functions but on the quantification of the health effects between different future scenarios. For completeness, the results calculated in this study using GEMM NCD + LRI are compared with those calculated using GEMM for five specific causes of death (5-COD)—ischemic heart disease, stroke, COPD, lung cancer, and LRI (see Text S3 in Supporting Information S1). This comparison shows that the main conclusions of this study remain unaffected by the choice of health assessment methodology.

The methodology to calculate the health impact associated with exposure to surface O_3 concentrations uses a hazard ratio for COPD mortality that matches the value used in the latest GBD 2019 study (Murray et al., 2020). The only health outcome associated with O_3 exposure considered in this study was mortality from COPD, consistent with the GBD 2019 methodology. Further details on the methodology for O_3 are provided in Text S2 in Supporting Information S1. The O_3 exposure values were calculated as 10-year mean population-weighted 6mMDA8 O_3 values from corrected UKESM1 simulation data.

The uncertainty ranges in our premature mortality estimates were calculated at the 95% confidence level (see Text S2 in Supporting Information S1). For $PM_{2.5}$, we used the derived uncertainty intervals from the exposure-outcome associations (Burnett et al., 2018). For O_3, we accounted for uncertainty in the hazard ratio by sampling 1,000 different effect estimates to derive a distribution in the attributable fraction for O_3 exposure (Conibear, Butt, Knote, Arnold, & Spracklen, 2018).

For each country, current and future cause-specific (NCD, LRI, and COPD) baseline mortality rates and population age structure for adults aged 25–80 years in 5-year age intervals and for 80 years plus were taken from International Futures (IFs) (Frederick S. Pardee Center for International Futures, 2021). We used current and future global gridded population count at a resolution of 0.125° × 0.125° from B. Jones and O'Neill (2016, 2020). Future changes in global population count follow the SSP3 pathway from B. Jones and O'Neill (2016, 2020). Future changes in baseline mortality rates and population age structure follow a middle-of-the-road "Base Case" scenario defined by IFs (S. Turner et al., 2017); https://pardeewiki.du.edu/index.php?title=Scenario_Analysis). We also performed sensitivity scenarios by fixing the baseline mortality rates, population age group and total population count at 2020 values to ascertain the impact of these factors on the calculation of the future air pollution health burden.

3. Results and Discussion

3.1. Change in Surface Air Pollutants

The bias corrected annual mean $PM_{2.5}$ concentrations and 6mMDA8 O_3 values for the present-day period (2005–2014) from UKESM1 are shown in Figures 1 and 2 respectively, along with the simulated changes in population weighted mean values across different regions (see Figure S1 in Supporting Information S1 for definition of regions) in the future scenarios. For further details on the changes in air pollutants in these future

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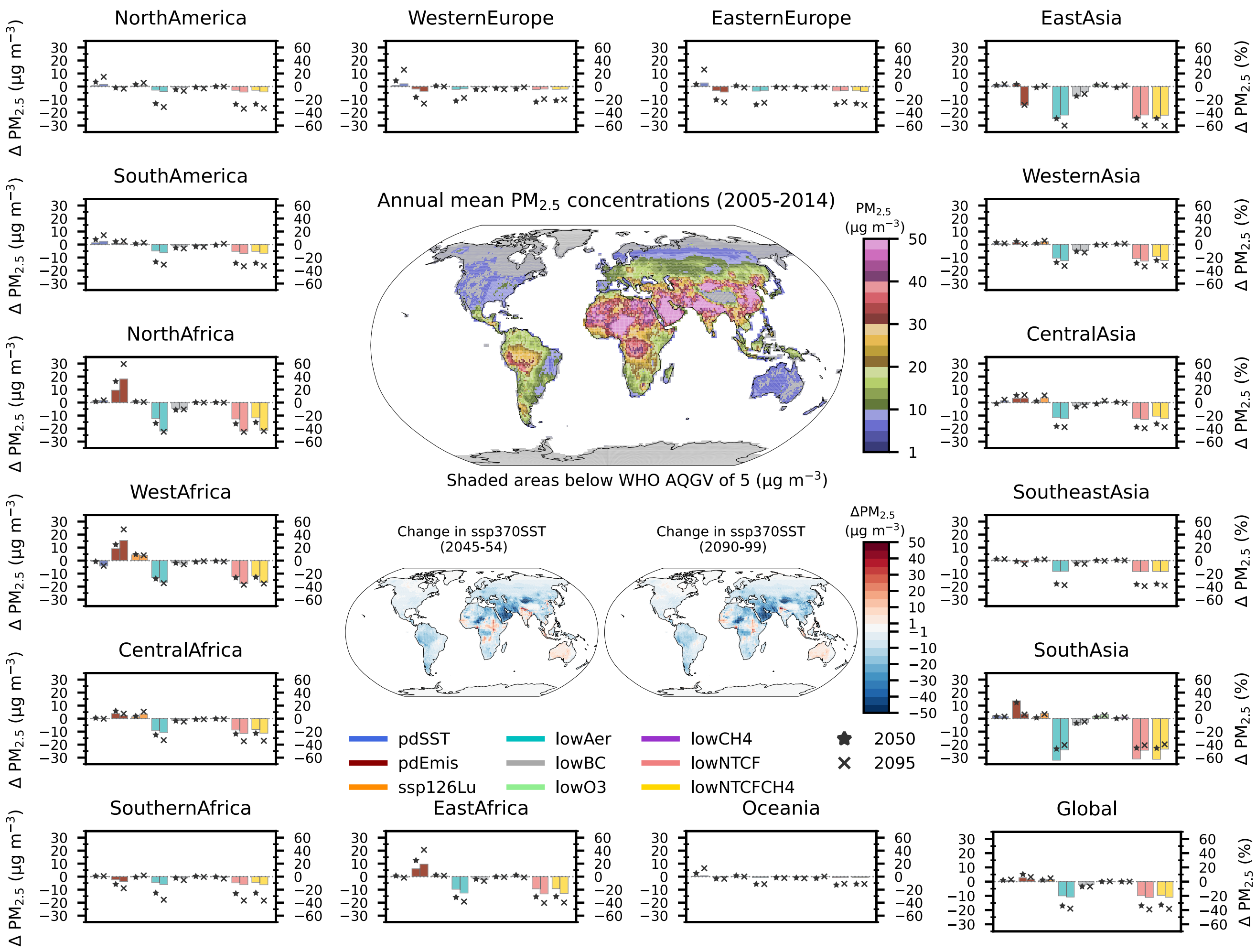

Figure 1. Annual mean corrected surface (land-only) $PM_{2.5}$ concentrations in UKESM1 averaged over a 10-year period (2005–2014) with gray shaded areas being below the World Health Organization air quality guideline value of 5 μg m^{-3} (center top panel) and concentrations over the ocean not plotted (white). Change in annual mean surface $PM_{2.5}$ concentrations in ssp370 scenario in 2045–2054 (center left panel) and 2090–2099 (center right panel) relative to 2005–2014 period. Regional change in annual mean $PM_{2.5}$ concentrations over a 10-year period centered on 2050 (left column) and 2095 (right column) for each sensitivity scenario relative to ssp370. The relative changes in the annual mean $PM_{2.5}$ concentrations are represented by the symbols (* for a 10 year mean value centered on 2050 and X for 2100).

scenarios, see Turnock et al. (2022). Most continental areas exceed the WHO AQGVs for $PM_{2.5}$ in the present day, with particularly elevated concentrations (>25 μg m^{-3}) across Africa, Middle East and Asia. If all NTCF emissions follow the trajectory of ssp370 instead of being fixed (pdEmis), then $PM_{2.5}$ concentrations can increase by ~50% (10 μg m^{-3}) over Africa, and by up to 10% (3.5 μg m^{-3}) over parts of Asia and South America. Nonetheless, $PM_{2.5}$ concentrations still reduce by ~20% in this scenario across Europe, North America, and East Asia due to the assumed continuation of policy measures to reduce air pollutant emissions in ssp370. However, large reductions in $PM_{2.5}$ concentrations of between 20% and 50% across most regions are shown by 2095 in the mitigation scenarios that involve a large decrease in aerosols and aerosol precursor emissions (lowAer, lowNTCF, and lowNTCFCH4). If only emissions of BC are reduced (lowBC) then $PM_{2.5}$ concentrations are simulated to reduce by 10% (~5 μg m^{-3}) across East and Western Asia, as well as North Africa. Mitigation of O_3 precursor emissions (lowO3) and methane (lowCH4) are shown to have little impact on changes in regional annual mean $PM_{2.5}$ concentrations in the future. If only future climate change is considered in isolation (pdSST), then surface $PM_{2.5}$ concentrations increase globally and across most regions. The largest increase of up to 25% (2.5 μg m^{-3}) in 2095 occurs across North America, Southern America, and Europe, and is mainly due to climate change increasing organic aerosols formed from biogenic VOCs (Turnock et al., 2022). There are small future changes in annual mean $PM_{2.5}$ concentrations across most regions resulting from land-use change (ssp126Lu). The largest increases

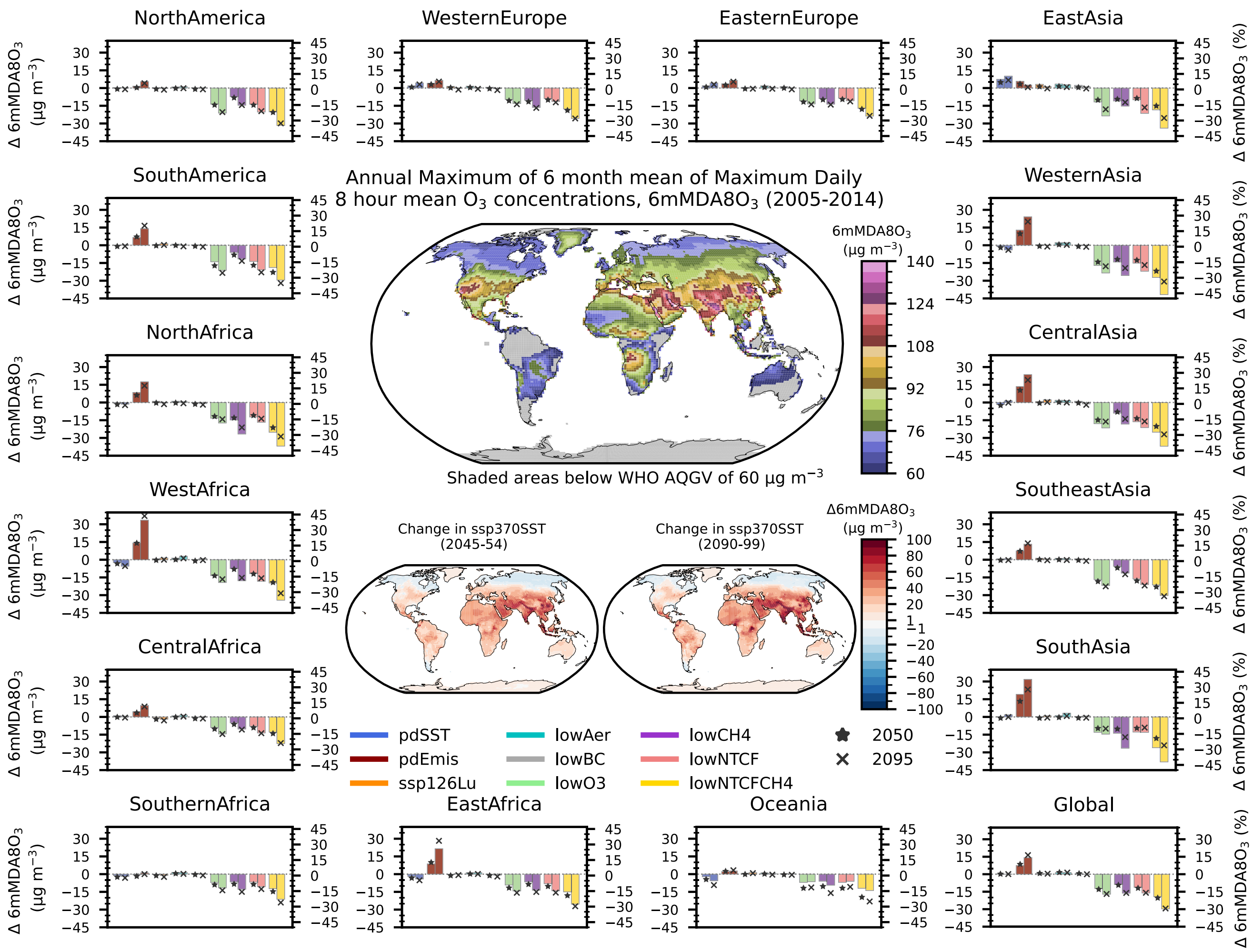

Figure 2. Corrected annual maximum of the 6-month running mean of the maximum daily 8 hr mean (land-only) O_3 value (6mMDA8) in UKESM1 averaged over a 10-year period (2005–2014) with shaded areas being below the World Health Organization air quality guideline value of 60 μg m^{-3} (center top panel) and concentrations over the ocean not plotted (white). Change in 6mMDA8 O_3 concentrations in the ssp370 scenario in 2045–2054 (center left panel) and 2090–2099 (center right panel) relative to 2005–2014 period. Regional change in 6mMDA8 O_3 concentrations over a 10-year period centered on 2050 (left column) and 2095 (right column) for each sensitivity scenario relative to ssp370. The relative changes in the 6mMDA8 O_3 concentrations are represented by the symbols (* for a 10 year mean value centered on 2050 and X for 2100).

of up to 10% (4 μg m^{-3}) in 2095 occur over West and Central Africa, and South, Central, and Western Asia due to changes in fine dust aerosol concentrations resulting from different land-uses (Turnock et al., 2022).

In the present-day (2005–2014) most continental areas are shown to exceed the WHO AQGVs for 6mMDA8 O_3, with particularly elevated concentrations (>80 μg m^{-3}) across parts of Asia, Middle East, Southern Europe, North America, and Southern Africa (Figure 2). In the future scenario that only considers the impact from future emissions of aerosols, O_3 precursors and global CH_4 concentrations in ssp370 (pdEmis) there is a large (up to 44% or 30 μg m^{-3}) increase in 6mMDA8 O_3 concentrations by 2095 across parts of Africa and Asia, driven mainly by the large changes in global CH_4. Large, combined decreases in global CH_4 concentrations and emissions of tropospheric O_3 precursors (lowNTCFCH4) result in large future reductions in 6mMDA8 O_3 of up to 35% (40 μg m^{-3}) by 2095 across all world regions. Similar, but smaller in magnitude, reductions in 6mMDA8 O_3 (up to 25% and 25 μg m^{-3} in 2095) result across all continental regions from individually reducing global CH_4 concentrations (lowCH4) and O_3 precursors (lowO3; NO_x, CO, and non-CH_4 VOCs), with the largest reductions across North and South America, and parts of Asia. However, reducing aerosols and aerosol precursor emissions results in a small increase in 6mMDA8 O_3 of up to 3% (3 μg m^{-3}) by 2095 across most regions due to a reduction in the sink for chemical reaction species involved in O_3 formation (Turnock et al., 2022). The scenario where future temperature increases due to climate change are considered in isolation (pdSST) do not change global mean 6mMDA8 O_3 concentrations by 2095. This is due to a balance between reductions of up to 8% (5 μg m^{-3}) in 2095 over regions remote from anthropogenic emission sources for example, Oceania, and increases of up to 9% (10 μg m^{-3}) in 2095 across polluted continental regions for example, East Asia and Europe. Land-use change (ssp126Lu) tends to result in small increases of 1%–2% in 6mMDA8 O_3 concentrations by 2095 across most regions, mainly over South America and parts of Asia, whereas there are some small reductions across Central and Southern Africa.

3.2. Air Pollution Health Burden in the Reference Scenario

Exposure to $PM_{2.5}$ concentrations in the present-day period (2005–2014) results in a global mortality burden in adults (people aged over 25 years) of slightly more than 6.8 million deaths per year (95% confidence interval, 95CI: 5.7–7.9 million, Table 2). This is smaller than the 8.9 million deaths per year (95CI: 7.5–10.3) predicted using the GEMM for 2015 by Burnett et al. (2018) because they use a different year and data source for annual mean ambient $PM_{2.5}$ concentrations, baseline mortality and population data. Estimates of the $PM_{2.5}$-attributable mortality burden using the GEMM are higher than other estimates, including the GBD, because the GEMM incorporates health responses from cohort studies in more countries that are conducted on human exposure to a wider range of ambient $PM_{2.5}$ exposure concentrations, rather than including cohort studies of second-hand smoke and household pollution with lower hazard ratio estimates (Burnett et al., 2022). In addition, the use of different underlying disease outcomes can impact the magnitude of mortality estimates from different health methodologies. The GEMM methodology used in this study considers non-accidental mortality, which produces larger estimates of air pollution attributable mortality than if cause-specific mortality rates were used (see Burnett et al. (2018) and Text S3 in Supporting Information S1). There are a number of different methods to estimate air pollution health burdens (Burnett & Cohen, 2020), all of which have limitations (Burnett et al., 2022) and are associated with large uncertainties (Nethery & Dominici, 2019), leading to a large range in global estimates (Pozzer et al., 2023). The use of different health response functions is attributed as being the main cause for the range of estimates in air pollution health burdens, followed by the type and number of health outcomes considered (Pozzer et al., 2023).

Future changes in the total global burden of $PM_{2.5}$ in ssp370, as simulated by UKESM1, increases the mortality in adults (>25 years) to 25.7 million deaths per year (95CI: 21.4–29.8) by 2100. This is likely an upper estimate of future increases in the mortality burden due to the assumptions on the underlying social, economic and air pollutant emission trajectories in ssp370. It is higher than that in other future SSPs (e.g., ssp126) due to the larger reduction in air pollutant concentrations (Turnock et al., 2020) and other changes in underlying health and demographic data (Yang et al., 2023). This increase in air pollution mortality in the ssp370 scenario is further shown by the change in global total adult $PM_{2.5}$ attributable mortality rate, which increases from 174 deaths per 100,000 (95CI: 144–201) in the present-day period to 284 deaths per 100,000 (95CI: 237–330) by 2100 (Table 2 and Table S1 in Supporting Information S1). Since the mortality rate per 100,000 normalizes for population growth, this increase is due to the changes in baseline mortality rates, the age structure of the population and population exposure to $PM_{2.5}$. Because the growth in global population weighted $PM_{2.5}$ concentrations is only 11% (Table 2), the largest contributor to future growth in $PM_{2.5}$ mortality is the change in baseline mortality rates and age structure of the population. The annual air pollution mortality rate in ssp370 increases across most regions between 2010 and 2100, with most of this occurring by 2060 (Figure S2 in Supporting Information S1) and the largest increase of more than 150 premature deaths per 100,000 people occurring across Asia and parts of Africa (Table S1 in Supporting Information S1). Only across Europe is the mortality rate projected to remain at or near present day values by 2100 in ssp370.

We calculate the present-day (2005–2014) air pollution health burden from exposure to ambient 6mMDA8 O_3 concentrations to be 295,000 (95CI: 248,000–341,000, Table 2) global premature mortalities due to COPD. Our estimates are smaller than the recent GBD estimates for 2017 exposure concentrations of 472,000 (95CI: 178,000–768,000) and for 2019 exposure concentrations of 365,000 deaths (95CI: 149,000–499,000) (Murray et al., 2020; Stanaway et al., 2018). From these numbers it can be seen that the present-day air pollution mortality burden from long-term exposure to surface O_3 concentrations is substantially less than that from $PM_{2.5}$ (see Table 2, and Pozzer et al. (2023)). Nevertheless, the global air pollution mortality burden from COPD in adults (>25 years) is estimated to increase to 3.5 million deaths per year (95CI: 3.0–4.0) by 2100 due to changes in

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Table 2
Global Pollutant Concentrations and the Global Total Air Pollution Health Burden for Exposure to Ambient $PM_{2.5}$ and O_3 in the Present-Day, Middle, and End of the 21st Century in Each of the Sensitivity Scenarios

Experiment	Time period	Global population weighted $PM_{2.5}$ concentration ($\mu g\ m^{-3}$)	Global premature adult mortality from exposure to $PM_{2.5}$ (95% confidence intervals)		Global population weighted 6mMDA8 O_3 concentration ($\mu g\ m^{-3}$)	Global premature adult mortality from exposure to O_3 (95% confidence intervals)	
			Total (millions)	Rate (100,000 per year)		Total (millions)	Rate (100,000 per year)
Historical	2005–2014	25.8	6.83 (5.68–7.92)	174 (201–144)	86.7	0.29 (0.25–0.34)	7.5(8.7–6.3)
ssp370SST	2045–2054	29.4	16.4 (13.7–19.0)	256 (296–214)	94.6	1.41 (1.19–1.62)	22 (25–19)
	2090–2099	28.6	25.7 (21.4–29.8)	284 (330–237)	101.2	3.50 (2.96–4.02)	39 (44–33)
pdSST	2045–2054	28.8	16.1 (13.5–18.7)	252 (291–210)	94.5	1.34 (1.13–1.54)	21 (24–18)
	ssp370SST—pdSST	+0.6 (2%)	+0.3 (2%)	+4 (2%)	+0.1 (0%)	+0.07 (5%)	+1 (5%)
	2090–2099	27.8	25.2 (21.0–29.3)	279 (324–232)	101.1	3.36 (2.84–3.85)	37 (43–31)
	ssp370SST—pdSST	+0.8 (3%)	+0.5 (2%)	+5 (2%)	+0.1 (0%)	+0.14 (4%)	+2 (4%)
pdEmis	2045–2054	26.6	15.6 (13.1–18.3)	246 (285–205)	87.2	1.09 (0.92–1.26)	17 (20–14)
	ssp370SST—pdEmis	+2.8 (11%)	+0.8 (5%)	+10 (4%)	+7.4 (8%)	+0.31 (29%)	+5 (29%)
	2090–2099	26.9	25.5 (21.2–29.6)	282 (327–235)	87.0	2.28 (1.92–2.63)	25 (29–21)
	ssp370SST—pdEmis	+1.7 (6%)	+0.2 (1%)	+2 (1%)	+14.2 (16%)	+1.22 (54%)	+14 (54%)
ssp126-Lu	2045–2054	30.0	16.5 (13.8–19.1)	257 (298–215)	95.3	1.44 (1.21–1.65)	22 (26–19)
	ssp126Lu—ssp370SST	+0.6 (2%)	+0.1 (1%)	+1 (0%)	+0.7 (1%)	+0.03 (2%)	0 (2%)
	2090–2099	30.0	26.5 (22.0–30.6)	292 (339–243)	101.7	3.55 (3.00–4.07)	39 (45–33)
	ssp126Lu—ssp370SST	+1.4 (5%)	+0.8 (3%)	+8 (3%)	+0.5 (1%)	+0.05 (1%)	0 (1%)
lowAer	2045–2054	19.3	12.0 (9.9–14.0)	187 (218–155)	96.1	1.46 (1.23–1.68)	23 (26–19)
	lowAer—ssp370SST	−10.1 (34%)	−4.4 (27%)	−69 (27%)	+1.5 (2%)	+0.05 (4%)	+1 (4%)
	2090–2099	17.7	18.9 (15.6–22.0)	208 (243–172)	102.6	3.64 (3.08–4.17)	40 (46–34)
	lowAer—ssp370SST	−10.9 (38%)	−6.8 (26%)	−76 (27%)	+1.4 (1%)	+0.14 (4%)	+1 (4%)
lowBC	2045–2054	27.3	15.7 (13.0–18.1)	244 (283–203)	95.2	1.43 (1.21–1.65)	22 (26–19)
	lowBC—ssp370SST	−2.1 (7%)	−0.7 (4%)	−12 (5%)	+0.6 (1%)	+0.03 (2%)	0 (2%)
	2090–2099	26.6	24.8 (20.6–28.8)	274 (318–228)	101.2	3.53 (2.99–4.05)	39 (45–33)
	lowBC—ssp370SST	−2.0 (7%)	−0.9 (4%)	−10 (4%)	0 (0%)	+0.03 (1%)	0 (1%)
lowO3	2045–2054	29.3	16.5 (13.8–19.1)	257 (297–215)	82.4	1.07 (0.90–1.24)	17 (19–14)
	lowO3—ssp370SST	−0.1 (0%)	+0.1 (1%)	+1 (0%)	−12.2 (13%)	−0.33 (24%)	−5 (24%)
	2090–2099	28.7	25.9 (21.6–30.1)	287 (332–239)	84.1	2.57 (2.17–2.96)	28 (33–24)
	lowO3—ssp370SST	+0.1 (0%)	+0.2 (1%)	+3 (1%)	−17.1 (17%)	−0.93 (27%)	−11 (27%)
lowCH4	2045–2054	29.3	16.4 (13.7–18.9)	255 (295–213)	85.8	1.09 (0.92–1.26)	17 (20–14)
	lowCH4—ssp370SST	−0.1 (0%)	0.0 (0%)	−1 (0%)	−8.8 (9%)	−0.31 (22%)	−5 (22%)
	2090–2099	28.6	25.8 (21.5–29.9)	286 (331–238)	85.0	2.32 (1.96–2.68)	26 (30–22)

Table 2
Continued

Experiment	Time period	Global population weighted $PM_{2.5}$ concentration ($\mu g\ m^{-3}$)	Global premature adult mortality from exposure to $PM_{2.5}$ (95% confidence intervals)		Global population weighted 6mMDA8 O_3 concentration ($\mu g\ m^{-3}$)	Global premature adult mortality from exposure to O_3 (95% confidence intervals)	
			Total (millions)	Rate (100,000 per year)		Total (millions)	Rate (100,000 per year)
	lowCH4—ssp370SST	0.0 (0%)	+0.1 (0%)	+2 (1%)	−16.2 (16%)	−1.18 (34%)	−13 (34%)
lowNTCF	2045–2054	19.4	12.0 (10.0–14.0)	188 (219–156)	83.4	1.09 (0.92–1.26)	17 (20–14)
	lowNTCF—ssp370SST	−10.0 (34%)	−4.4 (27%)	−68 (27%)	−11.2 (12%)	−0.31 (22%)	−5 (22%)
	2090–2099	17.4	18.7 (15.4–21.8)	206 (241–171)	85.1	2.65 (2.23–3.04)	29 (34–25)
	lowNTCF—ssp370SST	−8.9 (31%)	−7.0 (27%)	−78 (27%)	−16.1 (17%)	−0.85 (24%)	−10 (24%)
lowNTCFCH4	2045–2054	19.7	12.1 (10.0–14.1)	188 (219–156)	75.4	0.82 (0.69–0.95)	13 (15–11)
	lowNTCFCH4—ssp370SST	−9.7 (33%)	−4.3 (26%)	−68 (27%)	−19.2 (20%)	−0.59 (42%)	−9 (42%)
	2090–2099	17.6	18.8 (15.6–22.0)	208 (242–172)	71.5	1.61 (1.35–1.86)	18 (21–15)
	lowNTCFCH4—ssp370SST	−11.0 (38%)	−6.9 (27%)	−76 (27%)	−29.7 (29%)	−1.89 (54%)	−21 (54%)

Note. The mortality rate presented here is calculated only for the adult population (>25 years olds). The change relative to the reference scenario, ssp370, is also presented in each time period for each scenario.

O_3 simulated by UKESM1 and other socio-demographic factors in ssp370. The global adult mortality rate increases from 7.5 deaths per 100,000 (95CI: 6.3–8.7) in the present day to 39 deaths per 100,000 (95CI: 33–44) by 2100 (Figure S3 and Table S2 in Supporting Information S1). Like for $PM_{2.5}$, the future O_3 health burden calculated in ssp370 is likely an upper estimate, with larger improvements anticipated in other SSPs due to the larger reductions in surface O_3 concentrations (Turnock et al., 2020). The present day to 2100 change in the future air pollution health burden due to COPD from exposure to 6mMDA O_3 concentrations is dominated by the large increase of more than 50 premature deaths per 100,000 people across South Asia and East Asia (Table S2 in Supporting Information S1).

3.3. Impact of Mitigation Measures on the Air Pollution Health Burden

Figures 1 and 2 show the future changes in air pollutant exposure concentrations that are used here to calculate the impact on health burdens across each world region. Figure 3 (and Table S1 in Supporting Information S1) shows the changes in premature adult (>25 years) mortality rate (deaths per 100,000 people) from long-term exposure to $PM_{2.5}$ concentrations across different regions for all the future sensitivity scenarios, relative to the reference scenario ssp370. Using the change in adult (>25 years) mortality rate (normalizing per 100,000 people) provides a better comparison of the efficacy of different mitigation measures across regions by excluding the differences in total population size. Future scenarios that involve large reductions of aerosols and aerosol precursor emissions (lowAer, lowNTCF, and lowNTCFCH4) show large reductions in the rate of premature mortality associated with exposure to ambient $PM_{2.5}$ concentrations. Globally, the rate of premature mortality is reduced by approximately 27% (78 deaths per 100,000 people and 7 million total mortalities) in these scenarios by 2095, compared to the future reference scenario (ssp370). However, these potential health benefits are likely to be smaller than for other future SSPs for example, ssp126, which include additional future reductions in $PM_{2.5}$ concentrations by 2100 than in the mitigation scenarios used here (Turnock et al., 2020). The similarity between these three scenarios shows that reductions in aerosol emissions are the dominant driver of the change in $PM_{2.5}$ mortality. The largest benefit to human health is predicted to occur across East Asia, a 44% reduction in the rate of premature mortality (1.3 million total deaths reduced) by 2095. In these aerosol mitigation scenarios, most regions experience a benefit to human health of more than a 20% reduction in the rate of premature mortality. Reductions in future BC emissions (lowBC) can also have important impacts on the air pollution health burden across those regions with large present-day concentrations of BC for example, Asia. Solely decreasing BC emissions is predicted to reduce the rate of premature mortality by ~7% over Western Asia, East Asia, and North Africa. Across these regions the health benefits from reducing BC sources are important as they can make up more than one fifth of the total health benefits from reducing all anthropogenic sources of $PM_{2.5}$. However, the health calculation currently assumes equal toxicity from all components of $PM_{2.5}$, even though $PM_{2.5}$ from certain sources could have worse health effects than others (Lelieveld et al., 2015; Park et al., 2018).

In contrast to these future mitigation scenarios, the scenario that allows the effect due to the anthropogenic emissions trajectory of ssp370 to be isolated (pdEmis) shows regional disparities in the future air pollution health burdens. Long-term benefits to human health of up to a 20% reduction in

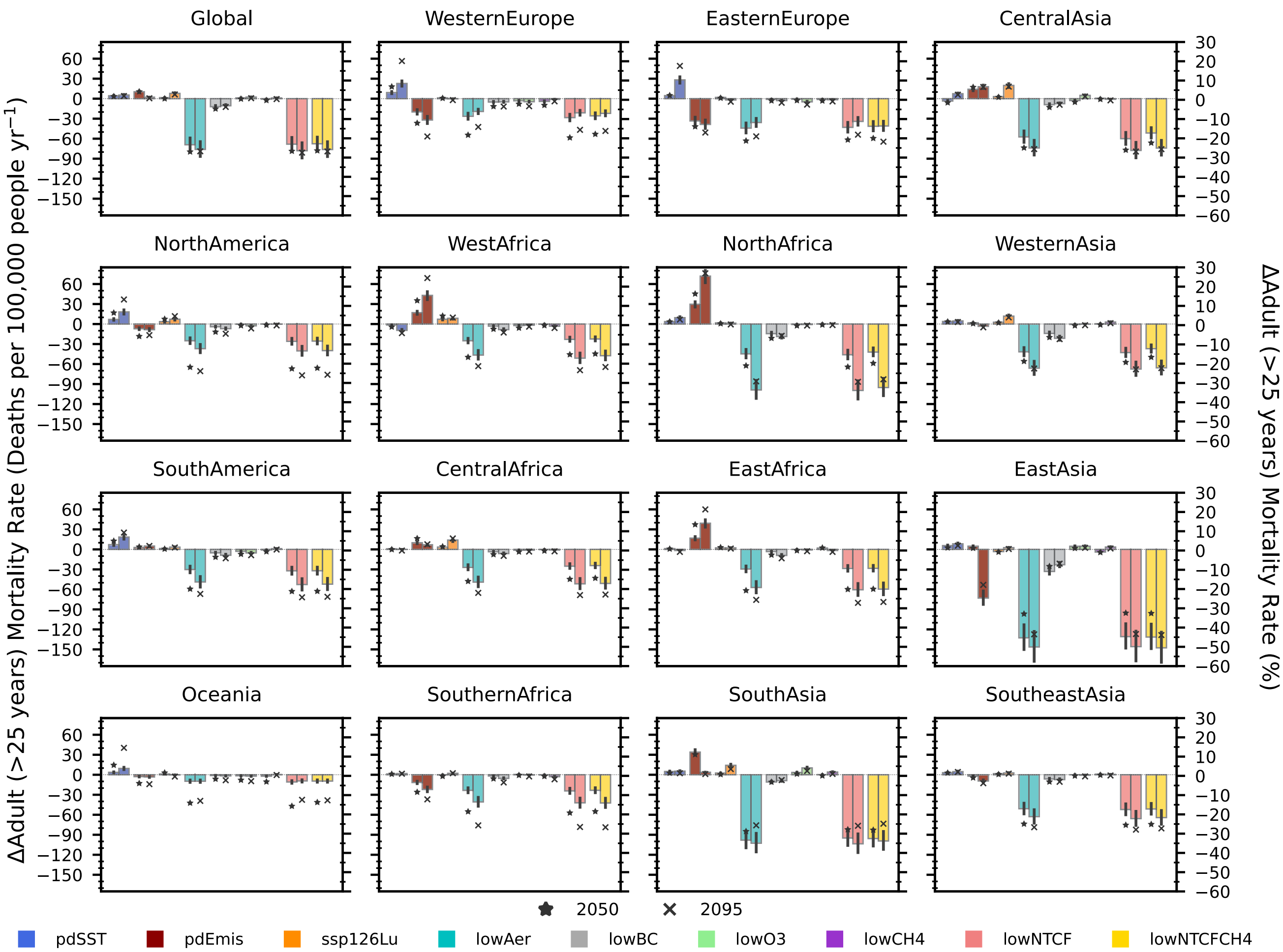

Figure 3. Regional change in the rate of annual premature adult (>25 years) mortality (deaths per 100,000 yr^{-1}) due to the change in exposure to annual mean surface $PM_{2.5}$ concentrations in UKESM1 averaged over a 10-year period centered on 2050 (left column) and 2095 (right column) across the different sensitivity scenarios, relative to the reference scenario ssp370. The relative change in the rate of annual premature adult (>25 years) mortality is represented by the symbols (* for a 10 year mean value centered on 2050 and X for 2100).

$PM_{2.5}$ attributable mortality are still predicted to occur across North America, Europe, and East Asia where there is a long-term trajectory to reduce air pollutant emissions in this scenario (Turnock et al., 2022). However, there are some detrimental impacts on health predicted to occur by 2050 across both East Asia (1%) and South Asia (11%), where air pollutant emissions are predicted to increase in the near-term but reduce over the long-term. Across Africa and Central Asia, air pollutant emissions are projected to increase in ssp370, resulting in the rate of premature mortality increasing by more than 20% (>40 deaths per 100,000 or >200,000 total mortalities) by 2095. Across these regions, the regional rivalry future scenario represents a penalty to future health burdens associated with increased exposure to ambient $PM_{2.5}$ concentrations.

The future scenario that allows the effect due to climate change to be isolated (pdSST) shows a detrimental impact on future air pollutant health burdens across North America, Europe, and South America from the large relative (but small absolute) increase (15%–25%) in $PM_{2.5}$ concentrations across these regions (Figure 1 and also in Fiore et al. (2022) and Im et al. (2022)). Across other regions there is a smaller relative impact on the $PM_{2.5}$ health burden from future climate change. Globally, climate change in ssp370 is predicted to result in ~488,000 (95CI: 408,000–564,000) $PM_{2.5}$ mortalities by 2095, relative to present climate, which is at the upper end of the previous estimate of the impact from climate change on $PM_{2.5}$ attributable mortality by Silva et al. (2017). However, there is still uncertainty about the sign and magnitude of the response of $PM_{2.5}$ in a future warming world, although it is thought more likely to be a climate penalty (Doherty et al., 2017; Fiore et al., 2015; Im et al., 2022; Jacob & Winner, 2009; Naik et al., 2021). Climate change increases the rate of premature mortality by more than

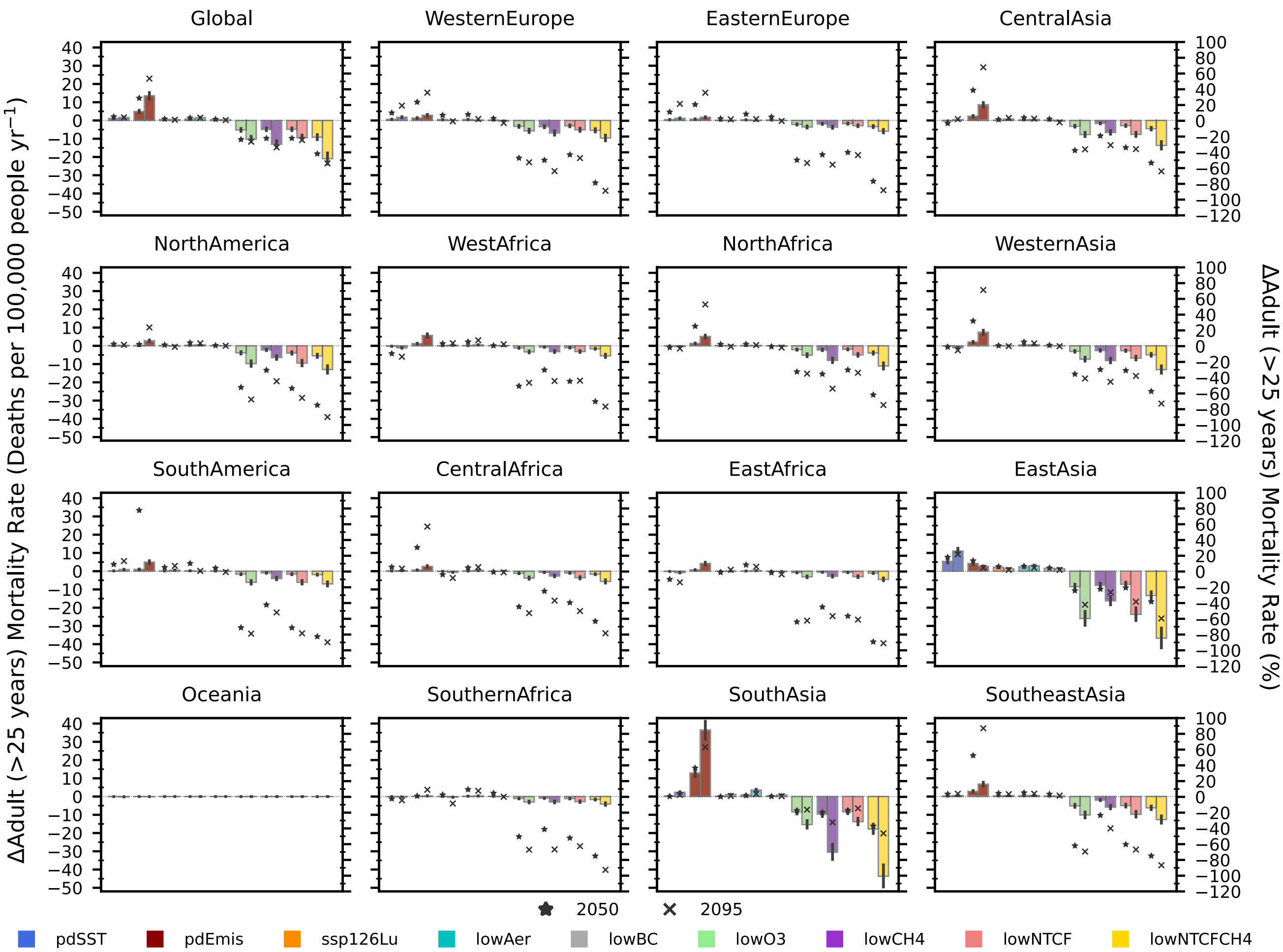

Figure 4. Regional change in the rate of annual premature adult (>25 years) mortality (deaths per 100,000 yr^{-1}) due to the change in exposure to 6mMDA8 O_3 concentrations in UKESM1 averaged over a 10-year period centered on 2050 (left column) and 2095 (right column) across the different sensitivity scenarios, relative to the reference scenario ssp370. The relative change in the rate of annual premature adult (>25 years) mortality is represented by the symbols (* for a 10 year mean value centered on 2050 and X for 2100). Note that relative changes are excluded from the figure for South America, West, and East Africa in pdEmis as the values are >100% and those for all scenarios for Oceania as the underlying values are small.

10% across North America, Europe, and South America by 2100 (Figure 3 and Table S1 in Supporting Information S1), offsetting some of the benefits achieved in the air pollutant mitigation scenarios (lowAer). Across Europe, the detrimental impact on human health from climate change (+18%) is large enough to completely offset any benefits from the mitigation scenario (−17%), indicating the importance of limiting climate change for regional air quality and health. The future land-use change scenario (ssp126Lu) results in some small increases (>5%) in the rate of premature mortality across Central Asia and Central Africa by 2095 due to the increase in exposure to larger ambient $PM_{2.5}$ concentrations from changes in land-use.

Figure 4 (and Table S2 in Supporting Information S1) shows the changes in premature adult (>25 years) mortality rate (deaths per 100,000 people) from long-term exposure to ambient 6mMDA8 O_3 concentrations across different regions for all future sensitivity scenarios, relative to the reference scenario ssp370. Large reductions in the rate of premature mortality associated with a reduced exposure to ambient 6mMDA8 O_3 concentrations occur in the future scenarios that involve large reductions of tropospheric O_3 precursor emissions (CO, NO_x, non-CH_4 VOCs—lowO3) and global CH_4 concentrations (lowCH4), as well as when these reductions are combined (lowNTCF and lowNTCFCH4). Globally, the rate of premature mortality is reduced by approximately 54% (amounting to a reduction of 21 deaths per 100,000 people and 1.9 million total mortalities) in the combined mitigation scenario (lowNTCFCH4) by 2095, in comparison to the future reference scenario (ssp370). However, other future SSPs for example, ssp126 are likely to lead to bigger health benefits due to the larger reductions in surface O_3 concentrations (Turnock et al., 2020) from the larger combined decreases in O_3 precursor emissions. Individually mitigating tropospheric O_3 precursor emissions and global CH_4 concentrations have similar magnitude of impacts on the global rate of premature mortality in 2095, reducing it by 27% (10 deaths per 100,000 people and >900,000 total mortalities) and 34% (13 deaths per 100,000 people and 1.2 million total mortalities), respectively. Regionally, the largest benefits to the air pollution health burden, a reduction of more than 25 premature deaths per 100,000 people by 2095, occurs across East and South Asia, regions with the highest present-day O_3 concentrations (Figure 2) and the largest baseline mortality rates to COPD. Across these parts of Asia, the mitigation of tropospheric O_3 precursors has a larger impact on 6mMDA8 O_3 concentrations and thus the health burden across East Asia, whereas changes to global CH_4 concentrations are more important for reductions across South Asia. Liu et al. (2022) showed with simulations of UKESM1 that the present-day chemical environment for near-surface O_3 production is different across East and South Asia and responds differently to future mitigation measures, which also leads to these differences in the response of the O_3 health burden. Changes in aerosols have also been shown to have important consequences for O_3 formation over Asia (Ivatt et al., 2022). Here, reducing aerosol and aerosol precursor emissions (lowAer) across South and East Asia results in small increases in 6mMDA8 O_3 concentrations due to the simulated reduction in the sink for chemical reaction species involved in O_3 formation, which increases the air pollution health burden by ∼4% (∼3 premature deaths per 100,000 and up to 90,000 total mortalities) by 2095. UKESM1 only includes a limited representation of the aerosol inhibition effect on O_3 formation and any changes to the O_3 health burden could be underestimated. Therefore, future changes in precursor emissions and chemical environment for O_3 production over different regions are important to consider when designing policies to achieve the maximum benefits to air pollutants and human health.

The future scenario that allows the effect due to the anthropogenic emissions trajectory of ssp370 to be isolated (pdEmis) shows a detrimental impact on the air pollution health burden across most regions by 2095, driven mainly by the large increase in global CH_4 concentrations. Particularly large impacts occur across South Asia, a region sensitive to changes in CH_4, where the rate of premature mortality increases by 63% (36 premature deaths per 100,000 and 925,000 total mortalities). Other regions show an increase of 1–9 premature deaths per 100,000, highlighting that any inaction to reduce future regional air pollutant emissions leads to a detrimental impact on the future air pollution human health burden from exposure to O_3.

Isolating the effect due to future climate change (pdSST) tends to result in a small detrimental impact on the air pollution health burdens across most regions due to an increase in exposure to ambient 6mMDA8 O_3 concentrations (Figure 2 and also in Brown et al. (2022) and Zanis et al. (2022)). The largest increase in 6mMDA8 O_3 concentrations from climate change occurs across East Asia which subsequently increases the rate of premature mortality by ∼20% (11 premature deaths per 100,000 and 94,800 total mortalities, Figure 4 and Table S2 in Supporting Information S1). This detrimental health effect across east Asia from climate change effectively offsets any benefits achieved from emission mitigation measures (lowO3) in the region. There are also some small increases in the rate of premature mortality due to climate change across Europe and South Asia. Future changes in land-use (ssp126Lu) result in small changes in ambient 6mMDA8 O_3 concentrations, which result in minimal impacts to the air pollution health burden across most regions.

3.4. Sensitivity of the Air Pollution Health Burden to Underlying Health and Demographic Data

Sensitivity scenarios were conducted on the air pollution health burden calculated for the reference scenario, ssp370, by fixing the underlying socio-economic drivers (baseline mortality—Fixed 2020 BM, population aging—Fixed 2020 age, total population—Fixed 2020 pop and $PM_{2.5}$ concentrations—Fixed 2020 $PM_{2.5}$ pop) at 2020 values for all future time periods (Figure 5). Globally, fixing baseline mortality rates in 2020 (Fixed 2020 BM) stops the improvement in the underlying health of a population and so the future air pollution mortality rates are larger, relative to ssp370, by just over 200 premature deaths per 100,000 people by 2095. Fixing the age structure of a population at 2020 levels (Fixed 2020 age) stops the general trend of populations getting older and reduces the global air pollution mortality rate by approximately 200 premature deaths per 100,000 people by 2095 as younger adults are less susceptible to health impacts from air pollution. Fixing the global total population count in 2020 (Fixed 2020 pop) stops any future population growth and the global air pollution mortality rate reduces by ∼100 premature mortalities per 100,000 people by 2095, due to the total adult (>25 years) population continuing to increase when mortality rates are calculated. This result is consistent with the response of decreasing total adult mortalities when the total global population count is fixed at 2020 values (Figure S4 in Supporting Information S1). Fixing the baseline mortality rate, population aging and total population together at

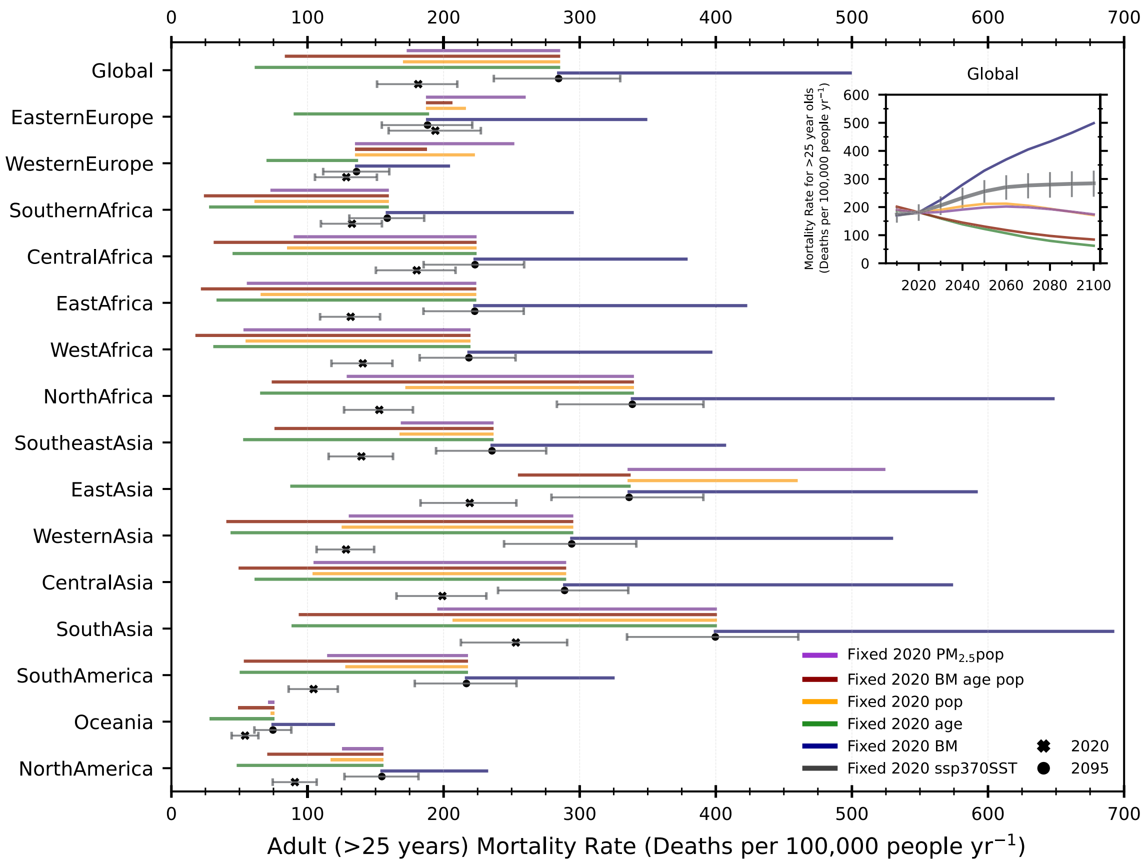

Figure 5. Regional total rate of annual adult (>25 years) premature mortality (deaths per 100,000 people yr^{-1}) due to the change in exposure to annual mean surface $PM_{2.5}$ concentrations in UKESM1 in 2020 (✖) and 2095 (●) of the ssp370 future scenario. The gray lines are error bars representing the upper and lower confidence intervals in the calculation of the human health air pollution burden. The change in the 2095 mortality rate in ssp370 is shown from fixing at 2020 values baseline mortality rate (blue), population aging (green), total population (yellow), all of the former combined (dark red), and $PM_{2.5}$ concentrations (purple). The inset shows the full global mean time series from the different scenarios considering the underlying health and demographic drivers (Figures S2 in Supporting Information S1 shows regional time series).

2020 values (Fixed 2020 BM age pop) has an overall effect of reducing the premature mortality rate by 2095. If the population weighted $PM_{2.5}$ concentrations are fixed at 2020 values and not allowed to increase (Fixed 2020 $PM_{2.5}$ pop), then the global air pollution mortality rate reduces by ∼100 premature mortalities per 100,000 people by 2095. Regionally, the largest impact on air pollution mortality rates in ssp370 is from changes in baseline disease mortality rates (Fixed 2020 BM) and population aging (Fixed 2020 age) occurring across North Africa, South Asia, East Asia and Central Asia, which is also consistent across other scenarios in Yang et al. (2023). Future changes in baseline disease mortality rates and the future aging of a population have large impacts, but of opposite sign, on the calculation of future air pollution health burdens, being responsible for 60% of the overall change. The influence of these changes should also be considered in addition to the air pollutant concentration changes in different future scenarios.

The sensitivity of the O_3 air pollution health burden due to COPD from different underlying socio-economic drivers has also been calculated and is shown in Figure S3 in Supporting Information S1. This shows similar sensitivities to the adult mortality rate as those for $PM_{2.5}$, although of smaller magnitude given the larger health impact from exposure to $PM_{2.5}$ concentrations. At a global scale, fixing the COPD baseline mortality rate in 2020 leads to a small increase in the future air pollution mortality rates compared to those in ssp370, limiting any future improvements to health. However, larger sensitivities in the O_3 air pollution health burdens were shown for fixing the age structure of the population and total population in 2020, which reduced the global O_3 mortality rate. The largest sensitivities in the O_3 air pollution health burden to the underlying socio-economic drivers occurs across south and east Asia. These are the regions with the largest baseline mortality rates for COPD and large total populations, experiencing different changes in these factors in the future.

4. Conclusions

Future mitigation policies targeting NTCFs can also affect air pollutants and their impacts on human health. Here we have used the change in air pollutant concentrations simulated by a single Earth system model (UKESM1) from a wide range of mitigation scenarios to assess the future impact on the air pollution health burden. The change in the air pollution health burden is quantified in scenarios that consider both the individual and combined mitigation of NTCFs, as well as isolating the impact from future transient changes in anthropogenic emissions, climate change and land-use change. This provides additional evidence of the potential impact from future mitigation of NTCFs, following a pathway toward implementing best available technology that achieve maximum reductions, on human health to help inform the design of such policies aligned to climate mitigation. The largest benefits (>25%) to the future air pollution health burden (for both $PM_{2.5}$ and O_3) are achieved in scenarios with large mitigation of all NTCFs (aerosols, O_3 precursors and CH_4), particularly over south and east Asia. Sensitivity scenarios show that the future air pollution health burden is considerably influenced by the assumed changes of baseline mortality rates and population aging within the scenario. However, if mitigation measures are not implemented and the anthropogenic emissions of the regional rivalry future scenario (ssp370) is followed then there are detrimental impacts on the air pollution health burden over south Asia in the near-term (2050) and across large parts of Africa by the end of the 21st century due to changes in both O_3 and $PM_{2.5}$. Individual NTCF mitigation scenarios highlight that reducing BC emissions can contribute up to 20% of the total benefits to the air pollution health burden over east Asia from reducing all emission sources of $PM_{2.5}$. However, the health calculation used here assumes equal toxicity from all components making up $PM_{2.5}$ and is also a non-linear function meaning that the impact on the air pollution health burden will depend on the sequence of implementation from different individual mitigation measures (Kodros et al., 2016). In addition, the mitigation of different individual O_3 precursors causes a difference in the magnitude of reduction of the O_3 health burden across East and South Asia, indicating that future changes in the chemical environment for O_3 production are an important consideration for achieving maximum health benefits. Reductions in aerosol concentrations over Asia are shown to lead to detrimental impacts on the O_3 air pollution health burden, in contrast to the large benefits to the $PM_{2.5}$ air pollution health burden. Future changes in climate are shown to have a regionally important impact on the air pollution health burden, with a detrimental impact over East Asia from increased exposure to O_3 and over Europe, North America and South America from increased exposure to $PM_{2.5}$. Over Europe and East Asia, the climate penalty on the air pollution health burden from exposure to ambient $PM_{2.5}$ and O_3, respectively is large enough to offset any benefits achieved from emission reduction measures, highlighting the importance of mitigating both climate and anthropogenic emission sources. Here we show the additional benefit to human health from reducing air pollutants in future climate scenarios that involve the mitigation of NTCFs, which should be taken into account when designing future policy measures. Important consideration needs to be given to the response over certain regions where future climate change could have important penalties and mitigating individual NCTFs induce a different magnitude of response.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The air pollutant data used in this study has been obtained from the CMIP6 data archive which is hosted at the Earth System Grid Federation and is freely available to download from https://esgf-node.llnl.gov/search/cmip6/. A list of the CMIP6 model diagnostics used in this study from each scenario are provided in Table S1 in Supporting Information S1, along with the relevant data citation for each experiment provided in Table S2 in Supporting Information S1 of the companion paper Turnock et al. (2022). Additional simulation data relevant to this publication from the non-AerChemMIP experiment ssp370SST-pdEmis is archived on Zenodo at the following location https://doi.org/10.5281/zenodo.5884604. The output quantifying the human health impact from the changes in the air pollution health burden from the different future scenarios is archived on Zenodo at the following location https://doi.org/10.5281/zenodo.7681849.

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