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The Future Climate and Air Quality Response From Different Near-Term Climate Forcer, Climate, and Land-Use Scenarios Using UKESM1

Steven T. Turnock[1,2], Robert Allen[3], Alex T. Archibald[4,5], Mohit Dalvi[1], Gerd Folberth[1], Paul T. Griffiths[4,5], James Keeble[4,5], Eddy Robertson[1], and Fiona M. O'Connor[1]

[1]Met Office Hadley Centre, Exeter, UK, [2]University of Leeds Met Office Strategic (LUMOS) Research Group, University of Leeds, UK, [3]Department of Earth and Planetary Sciences, University of California Riverside, Riverside, CA, USA, [4]Department of Chemistry, University of Cambridge, Cambridge, UK, [5]National Centre for Atmospheric Science (NCAS), University of Cambridge, Cambridge, UK

Key Points:

- Future changes in Near Term Climate Forcers have important implications for both air quality and climate
- Combined mitigation of aerosols and methane is required to achieve maximum co-benefits to both future air quality and climate
- Future changes in land-use and climate also impact the level of mitigation required to anthropogenic sources of near-term climate forcers

Supporting Information:

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

Correspondence to:

S. T. Turnock,
steven.turnock@metoffice.gov.uk

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Author Contributions:

Conceptualization: Steven T. Turnock, Fiona M. O'Connor
Formal analysis: Steven T. Turnock, Robert Allen, Alex T. Archibald, Gerd Folberth, Paul T. Griffiths, James Keeble, Fiona M. O'Connor
Methodology: Steven T. Turnock, Fiona M. O'Connor
Resources: Steven T. Turnock, Mohit Dalvi, Paul T. Griffiths, James Keeble, Eddy Robertson, Fiona M. O'Connor
Writing – original draft: Steven T. Turnock, Fiona M. O'Connor

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Abstract Near-term climate forcers (NTCFs) can influence climate via interaction with the Earth's radiative balance and include both aerosols and trace gas constituents of the atmosphere (such as methane and ozone). Two of the principal NTCFs, aerosols (particulate matter) and tropospheric ozone (O_3), can also affect local air quality when present in the lower levels of the atmosphere. Previous studies have shown that mitigation of NTCFs has the potential to improve air quality and reduce the rate of surface warming induced by long-lived greenhouse gases. Here, we assess the combined air quality and climate impacts from changes in NTCFs under numerous different future mitigation scenarios, relative to a future reference scenario, that were conducted by a single Earth system model (UKESM1) as part of the Aerosol and Chemistry Model Intercomparison Project (AerChemMIP). Co-benefits to both global air quality and climate are only achieved in the future scenario with strong mitigation measures applied to all NTCFs, particularly aerosols and methane, with penalties identified for inaction. When compared to the combined NTCF mitigation scenario, analysis of individual mitigation scenarios shows that there are important non-linearities and interactions between NTCFs (e.g., aerosols and clouds). If only aerosol components are mitigated, there are still benefits to air quality but detrimental impacts on climate, particularly at the regional scale. In addition, other changes in future land-use and climate could have important impacts on regional NTCFs, which should be considered when designing future mitigation measures to anthropogenic emissions.

Plain Language Summary Components of the Earth's lower atmosphere, such as methane, aerosols, and ozone, have an important influence on the rate by which the climate warms in the short-term (2050s) and are identified as near-term climate forcers (NTCFs). Elevated concentrations of these components at the surface can also lead to poor air quality and impacts on human health. Therefore, future strategies to reduce these components provide opportunities to benefit both the rate of climate warming and levels of air pollution. Using a global Earth system model, we simulate the combined impact on future climate and air quality from numerous different ways to reduce NTCFs. We show that the largest benefit to both future climate and air quality is achieved by reducing concentrations of methane and aerosols at the same time. If only aerosols are reduced, then this leads to a benefit to air quality but could accelerate the rate of near-term warming. However, when reducing NTCFs there are important interactions with the Earth system that need further consideration. Our findings highlight that reducing different NTCFs can have different impacts, particularly regionally, and that measures to benefit both future climate and air quality need to be carefully designed.

1. Introduction

Future pathways to mitigate climate change could have important impacts on the rate and magnitude of the surface temperature rise induced by long-lived greenhouse gases, as well as on regional air quality which has consequences for human health (Fan et al., 2020; Naik et al., 2021; Silva et al., 2016; Turnock et al., 2020). An important contribution to avoiding these negative impacts is made from near-term climate forcers (NTCFs), which are a collection of aerosol components and chemically reactive gases in the atmosphere that are relatively short-lived and exert an influence on the Earth's climate (through changes in the radiative balance) and affect air

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quality when present at the surface. Some of the major NTCFs with important impacts on both air quality and climate forcing are aerosols (including the components black carbon [BC], sulfate [SO_4^{2-}], nitrate [NO_3^-], and organic aerosols [OAs]), tropospheric ozone (O_3), and methane (CH_4). NTCFs can be emitted from both anthropogenic (e.g., fossil-fuel energy sources) and natural sources (e.g., dust or sea salt) or formed in the atmosphere through chemical reactions (e.g., O_3 formed from emissions of CH_4, carbon monoxide, CO and volatile organic compounds, VOCs in the presence of nitrogen oxides, NO_x).

The impact of these NTCFs on climate is important as the magnitude of their historical climate forcing due to anthropogenic changes is approximately equivalent to that from the long-lived greenhouse gas CO_2 (Forster et al., 2021; Myhre et al., 2013; Naik et al., 2021; Shindell et al., 2013). O'Connor et al. (2021) quantified the pre-industrial (1850) to present-day (2014) effective radiative forcing (ERF) in UKESM1 from changes in anthropogenic emissions of aerosols and aerosol precursor emissions (-1.09 ± 0.04 W m^{-2}), non-CH_4 O_3 precursor emissions ($+0.21 \pm 0.04$ W m^{-2}), and all non-CH_4 NTCFs (-1.03 ± 0.04 W m^{-2}). In addition, historical changes in global CH_4 concentrations and land-use in UKESM1 resulted in a global 1850 to 2014 ERF of $+0.97 \pm 0.04$ and -0.17 ± 0.04 W m^{-2}, respectively (O'Connor et al., 2021). Thornhill, Collins, Kramer, et al. (2021) presents similar 1850 to 2014 ERF results using output from multiple models participating in the sixth Coupled Model Intercomparison Project (CMIP6) based on changes in emissions of aerosols (-1.01 ± 0.25 W m^{-2}) and non-CH_4 O_3 precursors ($+0.20 \pm 0.07$ W m^{-2}). The CMIP6 multi-model study reported a slightly lower ERF for historical changes in global CH_4 abundance ($+0.67 \pm 0.17$ W m^{-2}) than occurred in UKESM1, mainly due to differences between how individual models represent tropospheric chemistry (including accounting for changes in CH_4 lifetime) and the rapid adjustments to clouds from CH_4 perturbations. The historical climate forcing from different NTCFs induced both a surface warming (BC, tropospheric O_3, and CH_4) and cooling (sulfate, nitrate, and OAs) of climate by both 0.5°C (Forster et al., 2021; Naik et al., 2021). NTCFs can also impact the hydrological cycle, altering regional precipitation patterns, including monsoon systems (L. Liu et al., 2018; Richardson et al., 2018; Samset et al., 2016). Therefore, future reductions in BC, CH_4, and tropospheric O_3 will cool the climate whereas reducing non-absorbing aerosols (sulfate, nitrate, and OAs) will warm the climate, as well as impact precipitation patterns (Allen, 2015; Andreae et al., 2005; Arneth et al., 2009; Kloster et al., 2010; Lelieveld et al., 2019; Samset et al., 2018; Westervelt et al., 2015).

Changes in climate can also impact NTCFs in numerous different ways (Doherty et al., 2017). In a future warmer world surface, O_3 concentrations are anticipated to increase over regions close to anthropogenic sources, the O_3 climate penalty (Colette et al., 2015; Rasmussen et al., 2013), and decrease over regions remote from major sources (Doherty et al., 2017; C. E. Johnson et al., 1999). Uncertainty in the future meteorological response due to climate change means that the response of aerosols is much more uncertain and regionally variable (Allen et al., 2016; Jacob & Winner, 2009; Shen et al., 2017). Some of the uncertainty in the future response of NTCFs to climate change arises because of the biogeochemical feedback from future changes in meteorological variables (temperature, water vapor, precipitation, clouds, and winds) on physiochemical processes in the atmosphere (e.g., chemical reaction rates) and also precursor emissions from natural sources such as sea salt (Carslaw et al., 2010; Doherty et al., 2017; Fiore et al., 2015; Heinze et al., 2019; Jacob & Winner, 2009). The latest Earth system models (ESMs) participating in CMIP6 have included numerous feedbacks between atmospheric chemistry, aerosols, and climate, which can act to enhance or dampen the climate response, although there is a large uncertainty in their sign and magnitude (Heinze et al., 2019; Naik et al., 2021; Thornhill, Collins, Olivié, et al., 2021). Thornhill, Collins, Olivié, et al. (2021) quantified the strength of aerosol and chemical feedbacks due to climate change from multiple CMIP6 models, showing that most feedbacks are negative (i.e., dampen any climate response) but have a large uncertainty between models. Important feedbacks include the positive feedback of CH_4 emissions from natural sources (Dean et al., 2018; O'Connor et al., 2010) and the negative feedback of biogenic volatile organic compounds (BVOCs) emissions from vegetation, precursors to OA and O_3, which can be impacted by future land-use change and changes in surface temperature and CO_2 concentrations (Heald & Spracklen, 2015; Pacifico et al., 2012; Scott et al., 2018; Unger, 2014a, 2014b). Therefore, future changes in climate and land-use could also have potentially important feedbacks on atmospheric composition at the surface and climate via changes to NTCFs.

At the surface, O_3 and fine particulate matter less than 2.5 μm in diameter ($PM_{2.5}$) are air pollutants. Elevated surface concentrations of these pollutants result in poor air quality with a detrimental impact on human health via respiratory, cardiovascular, cardiopulmonary, and lung disease. Historical changes in anthropogenic sources

of aerosols and O_3 have resulted in significant impacts on human health and ecosystems due to poor surface air quality (Butt et al., 2017; Cohen et al., 2017; Fowler et al., 2009). Globally, exposure to ambient concentrations of air pollutants (2015 concentrations of O_3 and $PM_{2.5}$) result in ~4 million premature mortalities per year (Cohen et al., 2017; WHO, 2016). Improving air quality by removing all fossil-fuel-related emissions of air pollutants (both aerosols and tropospheric O_3 precursors) could avoid 3.61 million attributable deaths per year (out of a revised total excess mortality rate of 8.79 million per year), as well as cause a slight warming of climate (Lelieveld et al., 2019). Future scenarios that include mitigation of NTCFs can reduce the amount of future warming, as well as benefit air quality and human health (Stohl et al., 2015). The large health impacts from exposure to NTCFs show that strong reductions are required to achieve improved air quality and health, as well as minimize any impact on future climate.

A number of recent studies have used the multi-model output from different experiments conducted as part of CMIP6, and in particular, the Aerosol and Chemistry Model Intercomparison Project (AerChemMIP), to provide an updated analysis of the different impacts from NTCFs (Allen et al., 2020, 2021; O'Connor et al., 2021; Thornhill, Collins, Kramer, et al., 2021; Thornhill, Collins, Olivié, et al., 2021; Turnock et al., 2020). Future scenarios that include strong mitigation of NTCFs showed improvements in surface air quality across all regions throughout the 21st Century, although a near-term climate warming occurred if measures only focused on aerosols and tropospheric O_3 precursors, excluding CH_4 (Allen et al., 2020; Turnock et al., 2020). A follow-up study by Allen et al. (2021) showed that including mitigation measures for CH_4 on top of those for of aerosol and non-CH_4 tropospheric O_3 precursors enhanced benefits to global air quality and offset the negative impacts on climate, resulting in a global surface cooling by 2100.

The above literature highlights that it is important to further understand the combined air quality and climate impacts occurring from future mitigation pathways, particularly with regard to minimizing the rate of future warming and reducing any impact on human health. Here, we extend the results of Allen et al. (2020, 2021) to assess the combined climate and air quality impacts in a wider range of sensitivity scenarios conducted as part of AerChemMIP by a single model (UKESM1) that includes a detailed representation of chemistry and aerosols coupled to other Earth system processes. An assessment of the impacts is made in scenarios that include individual mitigation of BC, CH_4, all aerosols and aerosol precursors and all non-CH_4 O_3 precursors, as well as from different combinations of the above. Additional sensitivity scenarios are also conducted to isolate the impact from future transient changes in climate, land-use, and all anthropogenic emissions.

2. Materials and Methods

2.1. Sensitivity Scenarios

AerChemMIP, is a CMIP6-endorsed Model Intercomparison Project, which seeks to understand past and future changes in atmospheric composition, and quantify the climate forcings and feedbacks of NTCFs (Collins et al., 2017). AerChemMIP selected the "Regional Rivalry" Shared Socio-economic Pathway (SSP) future scenario without climate policy, ssp370, as a reference scenario (Collins et al., 2017). This scenario has high challenges to mitigation and adaptation of future climate change resulting in a large future climate forcing (7.0 W m^{-2} by 2100), along with weak levels of air pollutant controls (Rao et al., 2017; Riahi et al., 2017). Therefore, any mitigation measures applied to the ssp370 scenario will allow for the largest response signal to be detected.

As part of the requested experiments for AerChemMIP, the fully coupled (atmosphere ocean) model simulations for the ssp370 pathway were repeated using prescribed sea surface temperatures (SSTs) and sea ice (SI) fields obtained from these fully coupled simulations, labeled as ssp370SST. In addition, vegetation distributions, leaf area index, and canopy heights are also obtained from the fully coupled model and used as prescribed inputs for the ssp370SST experiments. Individual mitigation measures are applied on top of this reference scenario, in accordance with those detailed in table 5 of Collins et al. (2017) and reproduced in Table 1 here. The sensitivity experiments are referred to in the rest of this study without the prefix ssp370SST and include reductions in emissions of BC (lowBC), all aerosol and aerosol precursors (lowAer—BC, OA, SO_2), all non-CH_4 O_3 precursors (lowO_3—CO, NO_x, non-CH_4 VOCs) and global CH_4 concentrations (lowCH_4). Additional scenarios are also included to ascertain the combined effect of reductions in emissions of aerosols, aerosol precursors, and non-CH_4 O_3 precursors (lowNTCF) and with CH_4 mitigation included on top (lowNTCFCH$_4$). The large emission reductions involved in these mitigation scenarios follow a pathway of cleaner air quality policies that are aligned with

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

	Anthropogenic air pollutant precursors				
Scenario	Aerosols	Ozone (non-CH_4)	Methane	Land-use	Climate
ssp370SST	Reference	Reference	Reference	Reference	Reference
lowNTCFCH$_4$	Clean	Clean	Clean	Reference	Reference
lowNTCF	Clean	Clean	Reference	Reference	Reference
lowCH$_4$	Reference	Reference	Clean	Reference	Reference
lowO$_3$	Reference	Clean	Reference	Reference	Reference
lowAer	Clean	Reference	Reference	Reference	Reference
lowBC	Clean (only for BC)	Reference	Reference	Reference	Reference
ssp126LU	Reference	Reference	Reference	ssp126	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

the SSP1 development pathway (Collins et al., 2017; Gidden et al., 2019). All other non-mitigated emissions or concentrations of aerosol and trace gases follow the reference scenario ssp370SST. Additional sensitivity scenarios have also been conducted with UKESM1 to assess the impact from future changes in climate (by keeping SSTs and SI fields based on a 2005 to 2014 climatology—pdSST), land-use (by replacing future land-use changes with those from the ssp126 scenario—ssp126LU), anthropogenic emissions (by fixing anthropogenic air pollutant precursor emissions and trace gas concentrations, including CH_4, at 2014 values—pdEmis). The pdEmis experiment has been conducted by UKESM1 in addition to the requirements of AerChemMIP. The land-use policies in the SSPs are described in Popp et al. (2017) and those contained in ssp126 reduce tropical deforestation and increase afforestation, increase crop yields over low and middle-income countries and have less pastoral land resulting from shift to healthier diets.

Comparing the results from the individual sensitivity scenarios shown in Table 1 to the reference pathway ssp370SST allows for an assessment of the impacts from the different measures on both climate forcing and air quality. To show if the differences are significant at the 95% confidence interval, a Student's *t*-test has been performed.

2.2. CMIP6 Models and Diagnostics

UKESM1 is a fully coupled ESM that includes a physical atmosphere ocean climate model coupled to an ocean biogeochemistry model, an interactive stratosphere-troposphere chemistry and aerosol scheme, as well as schemes for terrestrial carbon and nitrogen cycles coupled to an interactive vegetation model (Sellar et al., 2019, 2020). UKESM1 includes the coupling of various different natural emissions (e.g., BVOCs, dust, and sea salt) to atmospheric composition, allowing for an assessment of how earth system feedbacks from climate or land-use change impact atmospheric composition and climate (Archibald et al., 2020; Mulcahy et al., 2020). Therefore, UKESM1 is an appropriate model to use in studying the mitigation potential and impacts from changes to NTCFs and we use outputs from all the scenarios listed in Table 1 to quantify the effect on climate and air quality.

Monthly mean output of the CMIP6 diagnostics listed in Table S1 in Supporting Information S1 were obtained from UKESM1 for each of the scenarios listed in Table 1 over the whole simulation time period (2015–2099). As all the scenarios use an atmosphere-only configuration, then data is only available from a single model realization. Citations for the data used in this study are provided in Table S2 in Supporting Information S1. To assess the changes to NTCF emissions in each sensitivity scenario, relative to ssp370SST, the CMIP6 emission diagnostics were obtained for aerosol and aerosol precursors (BC, SO_2, OAs, dust, sea salt, and DMS), and tropospheric ozone precursors (CO, NO_x, non-CH_4 VOCs, BVOCs, and isoprene). Changes in CH_4 for each scenario are compared by using differences in the global CH_4 concentrations at the surface, used as the lower-level boundary

condition in UKESM1. To assess the impact on surface air quality from the different scenarios, monthly mean data was obtained from the lowest model level for O_3 and individual aerosol components of BC, SO_4^{2-}, OA (both primary and secondary), sea salt (SS), and dust (DU). For the results to be consistent with other studies using CMIP6 and AerChemMIP data (Allen et al., 2020, 2021; Turnock et al., 2020), an approximate method was used to calculate $PM_{2.5}$ concentrations. All aerosol mass of BC, SO_4^{2-} and OA, as well as 0.25 of sea salt and 0.1 of dust is assumed to be present within the 2.5 μm aerosol size fraction. UKESM1 does not currently include a representation of ammonium nitrate and as such has not been included in the $PM_{2.5}$ calculations, leading to an underestimation of the magnitude of $PM_{2.5}$ concentrations (Turnock et al., 2020). The approximate $PM_{2.5}$ is calculated using Equation 1.

$$PM_{2.5} = BC + OA + SO_4^{2-} + (0.25 \times SS) + (0.1 \times DU) \quad (1)$$

To calculate the impact on climate, we have calculated an ERF using the differences between the top-atmosphere (TOA) radiative fluxes (Table S1 in Supporting Information S1) in each sensitivity scenario compared to the reference scenario ssp370SST. This will yield the ERF due to composition changes in each sensitivity scenario. The pdSST scenario does not use identical SSTs like all of the other scenarios and therefore cannot be used to quantify an ERF from composition changes alone (as per the definition in Forster et al., 2016).

2.3. NTCF Emissions

The ssp370SST scenario was selected as the reference pathway and all sensitivity scenarios use the same socio-economic drivers (e.g., population and GDP change) as occur in the ssp370 scenario but with differing levels of NTCF emissions, as detailed in Table 1. For most scenarios, the implication is that NTCF mitigation measures (for both ozone, aerosols, and aerosol precursors) can be achieved under the socio-economic assumptions in ssp370. In addition, ssp370 has the highest future NTCF emissions of all the SSPs due to the assumed economic and technological changes (Gidden et al., 2019). Global NTCF emissions in ssp370 are shown to either increase or remain at or near present-day values by the end of the 21st century (Gidden et al., 2019; Turnock et al., 2020). However, there are differences at a regional level (regions defined in Figure S1 in Supporting Information S1) with emissions tending to reduce in ssp370 across North America, Europe, and East Asia, and increase across South Asia, Africa, Middle East, and parts of Central and South America (Figure S2 in Supporting Information S1 and within Turnock et al., 2020).

The change in global NTCF emissions in each sensitivity scenario compared to the reference ssp370SST scenario is shown in Figure 1. The sensitivity scenario showing the largest combined reductions in anthropogenic emissions is low$NTCFCH_4$. In this scenario global emissions of carbon monoxide (emico), nitrogen oxides (eminox), BC (emibc), and sulfur dioxide (emiso2) are reduced by approximately 50% in both the short (2050s) and long term (2090s). Slightly smaller reductions of ∼25% occur in the total source of OAs (emioa—both primary emissions and secondary formation of OAs). Large reductions also occur in global CH_4 concentrations, in comparison to ssp370SST, of 45% by the 2050s and ∼63% by the end of the 21st century. Other NTCF precursor emissions that are dominated by natural sources (emivoc, emibvoc, emiisop, emidms, emidust, and emiss) do not show any significant global change but can vary regionally. These global emission changes are also replicated across different regions and in other scenarios that only include a single mitigation measure (lowBC and lowCH_4) or a combination of measures (lowO_3, lowAer, and lowNTCF). By comparing these other scenarios to the total combined scenario, it is possible to separate out the influence of individual mitigation measures.

The impacts on NTCF emissions from solely climate change (pdSST), transient anthropogenic emissions (pdEmis), and land-use (ssp126Lu) are different to those of the mitigation scenarios discussed in the above paragraph. Climate change (calculated as ssp370SST − pdSST) increases the global emission of BVOCs in UKESM1, particularly isoprene, by up to 15% in the 2050s and by 30% in the 2090s due to the increased emissions from vegetation under higher future temperatures, despite the inhibition effect from rising CO_2 concentrations (Pacifico et al., 2012). Particularly large changes in BVOCs emissions occur over northern hemisphere mid-latitude regions, as well as tropical regions of South America, Africa, and Asia (Figure S3 in Supporting Information S1). In addition, the total source of OAs (emioa) increases by similar amounts as BVOCs due to future climate change, driven by an ∼50% increase in the secondary production of OAs in 2095. The increases in OA sources also tend to be concentrated across northern hemisphere mid-latitude regions, as well as South Asia, Central America, and South America (Figure S3 in Supporting Information S1). Other natural emission

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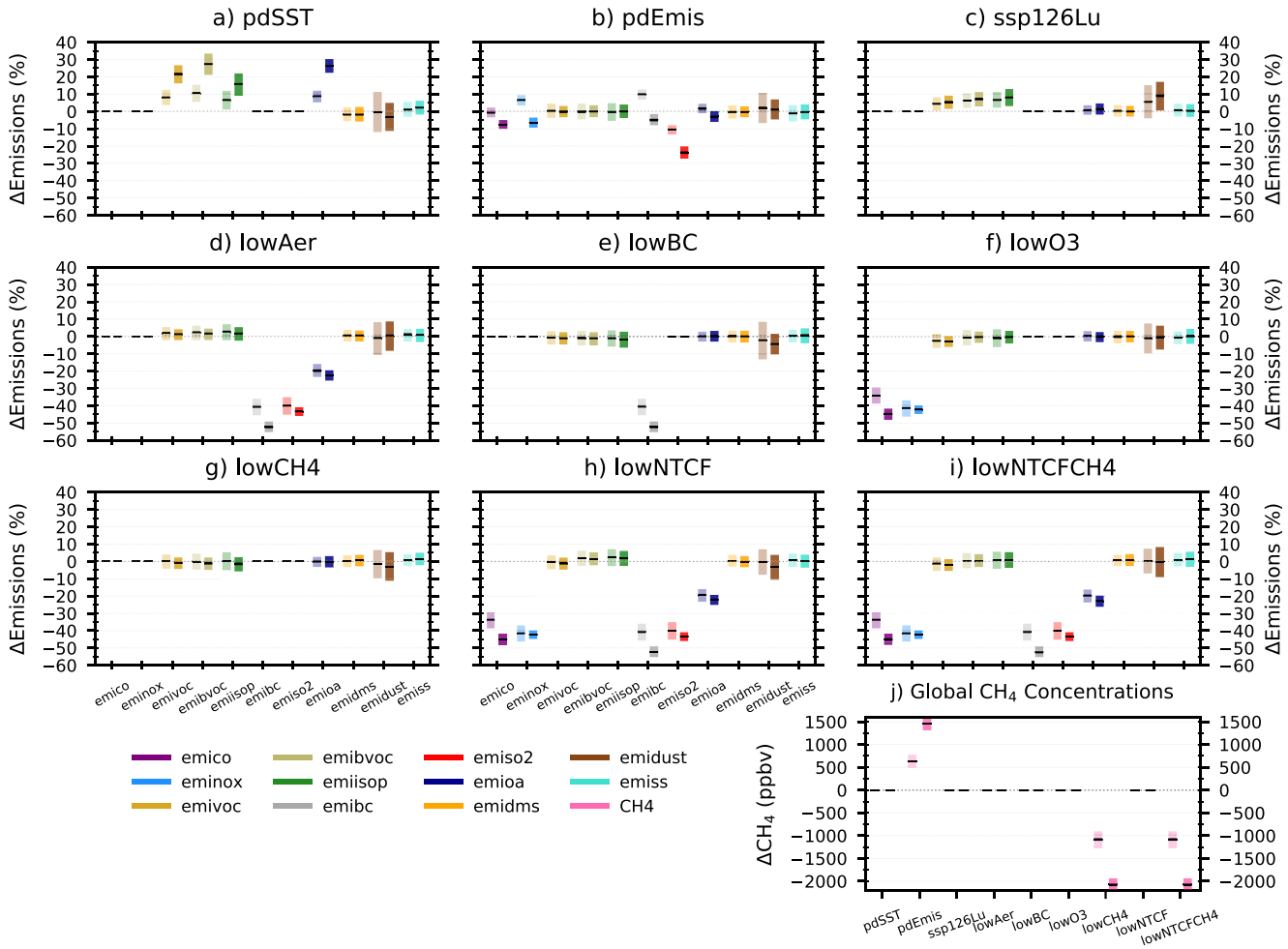

Figure 1. Global annual mean change in emissions of aerosols and precursors of aerosols and ozone for each sensitivity scenario in (a)–(i) relative to values in ssp370SST. Changes from climate change (a) and transient anthropogenic emissions (b) are calculated as values in ssp370SST relative to those in the pdSST and pdEmis scenarios, respectively. Changes in global annual mean methane concentrations are shown for each sensitivity scenario in (j). For each emission type, the bar represents the change in values over a 10-year period (centered on 2050 for the left-hand bar and 2095 for the right-hand bar), with the line representing the mean over this period and the bars being ±1 S.D.

sources show little impact from climate change at the global scale but are affected more regionally. Figure S3 in Supporting Information S1 shows that future climate change results in a large increase of DMS and sea salt emissions across both polar regions. Future climate change increases dust emissions across Europe, Russia, and Central America but reduces dust across Central and Eastern Asia, as well as the Middle East.

Isolating the impact from only transient future changes in anthropogenic air pollutant precursor emissions (ssp370SST − pdEmis) shows that global emissions of NO_x and BC will increase in the 2050s by up to 10% but then decrease by a similar amount at the end of the century (Figure 1b). Global emissions of CO and OAs remain near present-day values in the 2050s but decrease out to the end of the 21st century. In contrast, global emissions of SO_2 decrease by 10% in the 2050s and up to 30% by the 2090s. Global concentrations of CH_4 also increase out to 2100 in line with the ssp370 pathway (Figure 1j). There are significant spatial variations driving these global changes in future anthropogenic emissions, with reductions across northern hemisphere mid-latitudes (Europe and Norther America) and increases across the Middle East and tropical areas of Asia, Africa, and the Americas (Figure S4 in Supporting Information S1).

Implementing the land-use change policies associated with the ssp126 scenario in the ssp370SST scenario (ssp126Lu) increases the global emissions of BVOCs from vegetation, in particularly isoprene, by up to 10% by 2100 (Figure 1c). Large regional increases in BVOCs occur across Southern Africa, with smaller increases over

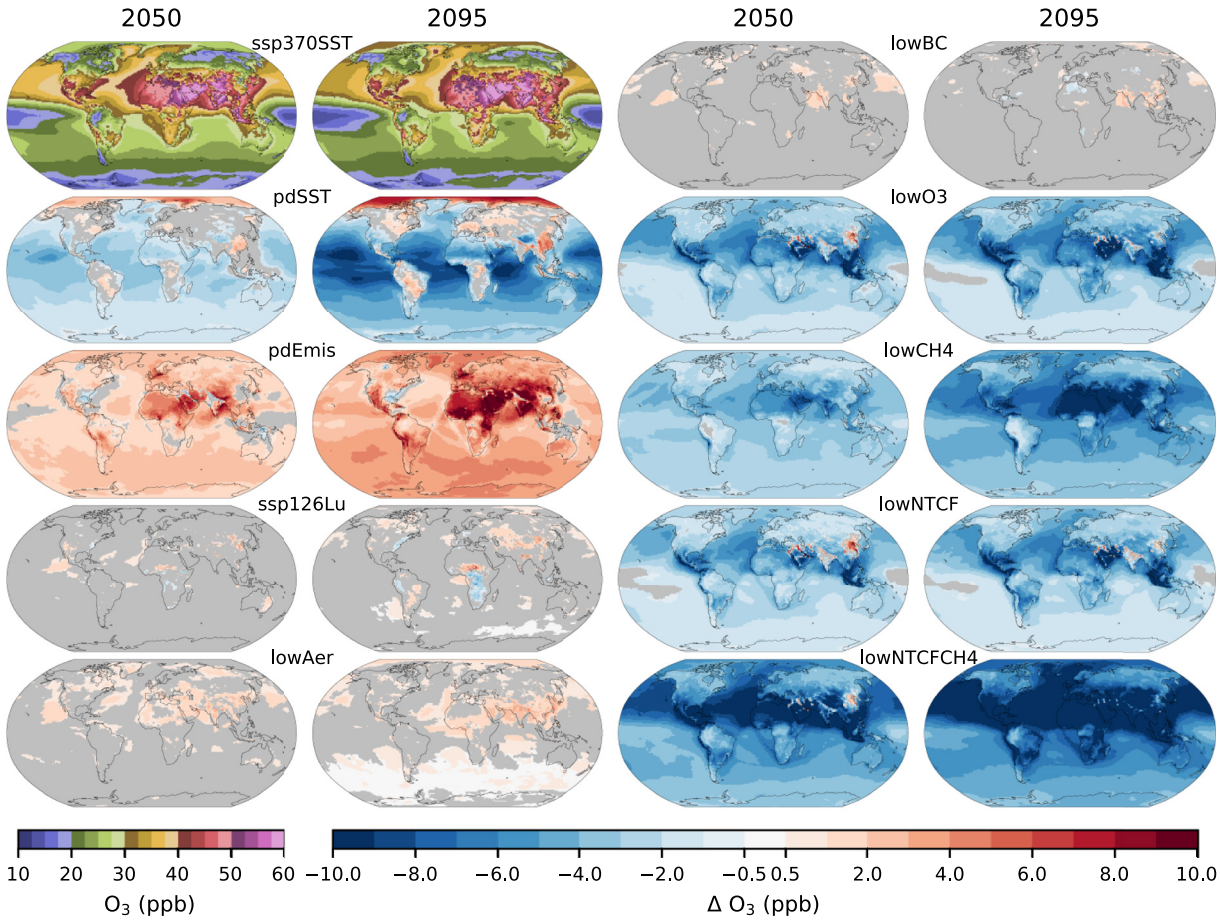

Figure 2. Annual mean change in surface O_3 from UKESM1 in each scenario relative to ssp370SST, apart from scenarios considering changes in climate and transient anthropogenic emissions which are calculated as values in ssp370SST relative to those in pdSST and pdEmis, respectively. The first two panels in the top row represent the 10-year annual mean surface O_3 concentrations in ssp370SST centered on 2050 (left column) and 2095 (right column). The remaining panels represent the change in each scenario as a 10-year mean centered on the same years in each column. Differences that are not statistically significant at the 95% confidence interval using a Student's *t*-test have been shaded gray.

South America, North America, and Europe (Figure S5 in Supporting Information S1). Global dust emissions also increase by approximately 10%, with increases over North America, Russia, Central Asia, East Asia, South America, Southern Africa, and South Asia (Figure S5 in Supporting Information S1 due to the change in land-use in the ssp126Lu scenario. While the global sources of OAs (both primary and secondary) are relatively unaffected by the different land-use scenario, regionally their emissions tend to reduce over the northern hemisphere mid-latitudes and increase across South America and Southern Africa (Figure S5 in Supporting Information S1). Other global NTCF emissions are relatively unaffected by the land-use change scenario.

3. Results

3.1. Surface Air Quality

3.1.1. Ozone

The simulated change in annual mean (averaged over 10 years) surface O_3 concentrations for each of the different sensitivity scenarios is shown in Figure 2 for the near-term (centered on 2050) and end of the 21st century (centered on 2095) time horizon. The strong NTCF mitigation scenario of lowNTCFCH$_4$, with large decreases in global CH_4 concentrations and emissions of tropospheric O_3 precursors (Figure 1), shows substantial reductions in global annual mean surface O_3 of 6 ppb (~20% of initial 30 ppb) in 2050 and 8 ppb (27% of initial 29 ppb) by 2095. These results are at the lower end of the multi-model mean range from five CMIP6 models reported in

Allen et al. (2021). The largest reductions, of more than 10 ppb, occur in the lower latitude northern hemisphere regions of Central America, Asia, and the Middle East (Table S3 in Supporting Information S1).

The individual drivers leading to this response in surface O_3 can be disentangled by analyzing the results from each of the individual mitigation scenarios. Reducing global CH_4 concentrations (lowCH_4) results in a decrease in annual mean surface O_3 concentrations, concentrated across the northern hemisphere, with global mean values reducing by 18% in 2095. The reduction in tropospheric O_3 precursor emissions (lowO_3—NO_x, CO, and non-CH_4 VOCs) also reduces annual mean global surface O_3 concentrations by 13% globally in 2095 and across similar regions as in lowNTCFCH$_4$. The reduction in O_3 tends to peak around the 2050s, coinciding with the peak in emissions mitigation (Figure 1). However, the reduction in O_3 precursor emissions, particularly NOx, leads to an increase in surface O_3 concentrations in 2050 over South Asia and Eastern China. This results from a decrease in titration of O_3 due to lower NO_x and an enhancement in O_3 from small increases in anthropogenic non-CH_4 VOCs over these regions (Z. Liu et al., 2021 and fig. 2 of Turnock et al., 2020). In contrast, reducing aerosols and aerosol precursor emissions (lowAer), results in some small significant increases in annual mean surface O_3 concentrations by 2095, mainly across the Middle East (3%), East Asia (3%), and South Asia (3%). In UKESM1, reducing aerosols results in a significant increase in the annual mean N_2O_5 surface concentrations and a reduction in HNO_3 concentrations across the Middle East and Asia (Figures S6 and S7 in Supporting Information S1), implying less heterogeneous loss of nitrogen oxides on aerosols (via $N_2O_5 + H_2O \rightarrow HNO_3$) and an increase in surface O_3 formation (Archibald et al., 2020). The change in global annual mean surface O_3 concentrations from the combination of individual mitigation scenarios is found to be within 10% of the response when perturbations are performed simultaneously in a single experiment (lowNTCFHC4), indicating that any nonlinearities are relatively small on a global basis. The overall response in global surface O_3 from mitigation scenarios is found to be ∼50% due to changes in CH_4, ∼40% from changes in O_3 precursors, and ∼10% from aerosols. However, these discrepancies in the linear combination from individual NTCF mitigation become larger on a regional level indicating that nonlinear chemistry effects are more important at this scale.

In the climate change only scenario (ssp370SST − pdSST), annual mean surface O_3 concentrations reduce, globally by 13% in 2095 over regions remote from large sources of anthropogenic pollution (Table S3 in Supporting Information S1). This reduction is attributed to the increased amounts of water vapor in a warmer world, ∼5°C by 2100 relative to the present day in UKESM1, leading to more hydroxyl formation and enhanced loss of O_3 in the absence of major sources of pollution, namely NO_x (Doherty et al., 2013; Fiore et al., 2012; C. E. Johnson et al., 1999; Zanis et al., 2022). However, UKESM1 also simulates that climate change will enhance local net O_3 production rates and increase annual mean surface O_3 concentrations (up to 5 ppb by 2095) across polluted continental regions of north east United States, central Europe, northern India, and eastern China. This is a stronger response than occurs in other CMIP6 models and could be due to the larger temperature response simulated by UKESM1 (Zanis et al., 2022). A small increase in annual mean surface O_3 concentrations (up to 2 ppb by 2095) is simulated across the major biogenic (low NOx) regions by UKESM1, although not by all CMIP6 models (Zanis et al., 2022), due to the enhancement of BVOC emissions from increasing temperatures (Figure S3 in Supporting Information S1). The increase in annual mean surface O_3 concentrations of 2.5 ppb (9%) across the Arctic by 2100 is attributed to a dynamically induced enhancement of the stratosphere-troposphere exchange process of O_3 resulting from climate change (Zanis et al., 2022).

The large increase in annual mean surface O_3 concentrations (>10% in 2095 across the Middle East and Asia) from only future transient changes in anthropogenic emissions in the ssp370 scenario (ssp370 − pdEmis) is mainly driven by the large increase in global CH_4 concentrations. This global change masks any regional impact, both increases and decreases, on surface O_3 from the future transient changes in regional O_3 precursor emissions NO_x, CO, and non-CH_4 VOCs (Figure S4 in Supporting Information S1).

The land-use change scenario (ssp126Lu) results in small increases in annual mean surface O_3 of up to 1 ppb (3%) across parts of South America, Africa, and Asia by 2095 but also some small decreases across sub-Saharan Africa, north-eastern United States and north-western South America (Figure 2 and Table S3 in Supporting Information S1). The ssp126Lu scenario results in an increase in the fraction of tree cover (Figure S8 in Supporting Information S1) and an increase in BVOC (isoprene) emissions, due to the coupling present in UKESM1 (Figure S9 in Supporting Information S1), over southern Africa, eastern United States and parts of South America. Over southern Africa and north-western South America, the increase in BVOCs reduces annual mean surface O_3 concentrations as isoprene more efficiently destroys O_3 in low NO_x environments (Pacifico et al., 2012).

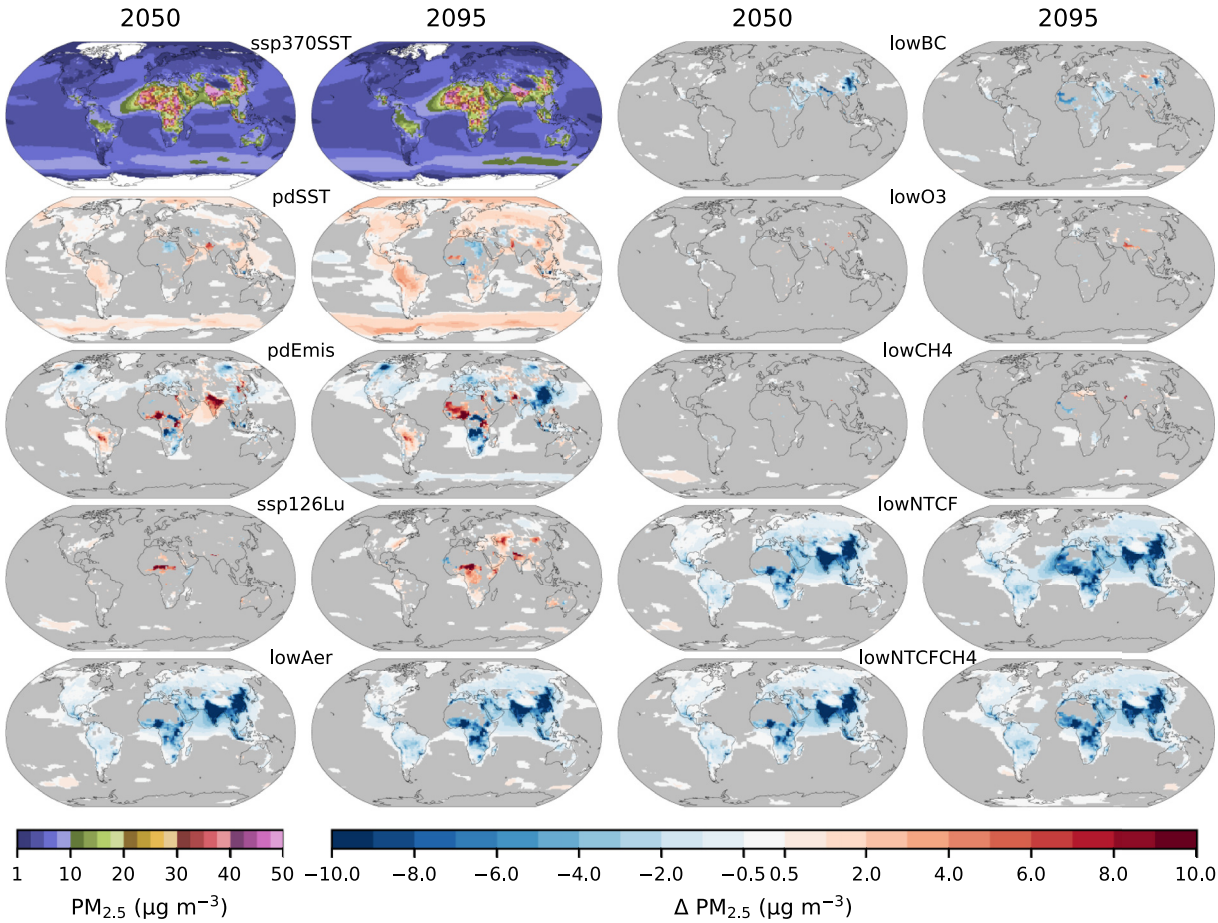

Figure 3. Annual mean change in surface $PM_{2.5}$ from UKESM1 in each scenario relative to ssp370SST, apart from scenarios considering changes in climate and transient anthropogenic emissions which are calculated as values in ssp370SST relative to those in pdSST and pdEmis, respectively. The first two panels in the top row represent the 10-year annual mean surface $PM_{2.5}$ concentrations in ssp370SST centered on 2050 (left column) and 2095 (right column). The remaining panels represent the change in each scenario as a 10-year mean centered on the same years in each column. Differences that are not statistically significant at the 95% confidence interval using a Student's *t*-test have been shaded gray.

However, over other parts of South America, the opposite response is true. In the higher NOx environment of the north-eastern United States, reductions in annual mean surface O_3 result from enhanced O_3 dry deposition rates (Figure S10 in Supporting Information S1) due to increased tree cover. Across other regions, the response of surface O_3 to land-use change can be attributed to a combination of factors, including natural emissions (BVOCs), O_3 dry deposition rates, surface albedo, and local meteorology. The atmospheric chemistry response to land-use change is complicated, regionally dependent and requires further investigation using multiple models and specific experiments to unpick the different drivers of regional change.

3.1.2. Fine Particulate Matter ($PM_{2.5}$)

Figure 3 shows the same result as Figure 2 but for surface $PM_{2.5}$ concentrations. Scenarios involving strong mitigation of aerosols and aerosol precursor emissions (lowAer, lowNTCF, and lowNTCFCH$_4$, Figure 1) result in large reductions of global annual mean $PM_{2.5}$ of 0.8 μg m^{-3} (11% of initial 7.0 μg m^{-3}) in 2050 and ∼1 μg m^{-3} (12% of initial 6.8 μg m^{-3}) by 2095. These results are anticipated to be slightly underestimated due to the absence of ammonium nitrate aerosols within UKESM1. However, they are of similar magnitude to the multi-model mean change from five CMIP6 models reported in Allen et al. (2020, 2021), which also showed that including ammonium nitrate would lead to additional reductions in $PM_{2.5}$. The largest reductions in $PM_{2.5}$ concentrations occur across southern Africa (30%), South East Asia (30%), East Asia (>40%), and South Asia (>35%) in both time periods (Table S4 in Supporting Information S1). Benefits to $PM_{2.5}$ concentrations from only reducing BC emissions (lowBC) are larger in the 2050s and concentrated across the Middle East (9%), East Asia (11%), and South

Asia (7%); regions with large present-day emissions. The lowO_3 and lowCH_4 scenarios did not have a significant impact on annual mean $PM_{2.5}$ concentrations. In a similar way to surface O_3, the change in global annual mean surface $PM_{2.5}$ concentrations from the combination of individual mitigation scenarios (e.g., lowO_3, lowAer, and lowCH_4) is found to be within 10% of the response from when perturbations are performed simultaneously in a single experiment (lowNTCFHC4). The response in surface $PM_{2.5}$ is more directly related to the emission perturbations of aerosols and aerosol precursors, although there is likely be an impact from changes in chemistry due to changes in O_3 precursors. However, these discrepancies in the linear combination are likely to become larger at the regional scale where more variability exists in the response of certain aerosol (e.g., dust) and chemical components.

Future climate change in the ssp370 scenario (ssp370SST − pdSST) increases annual mean surface $PM_{2.5}$ concentrations in both 2050 and 2095 across many regions, and by 7% in 2095 globally. Increases in annual mean $PM_{2.5}$ concentrations of up to 50% by 2095 occur across the polar oceanic regions, associated with enhanced emissions of sea salt aerosols (Figures S3 and S11 in Supporting Information S1) due to future climate change (higher future surface temperatures, reduction in sea ice and changes in high latitude surface winds) and are consistent with the CMIP6 multi-model response in Thornhill, Collins, Olivié, et al. (2021). Future climate change results in smaller increases in annual mean $PM_{2.5}$ concentrations across Europe, North America, Asia, and South America, due to increases in OAs (Figure S12 in Supporting Information S1), particularly secondary organic aerosols (SOAs). Higher future temperatures increase emissions of BVOCs from vegetation (Figure S3 in Supporting Information S1) across these regions, which are coupled to SOA formation in UKESM1 through monoterpenes (Mulcahy et al., 2020), enhancing $PM_{2.5}$ concentrations. Future climate change causes a small reduction (<2%) in annual mean surface $PM_{2.5}$ concentrations by 2095 across North Africa and the Middle East due to a reduction in fine dust aerosols (Figure S13 in Supporting Information S1). However, the response of dust is uncertain across all the CMIP6 models due to differences in the simulated response of vegetation and meteorology to climate change (Thornhill, Collins, Olivié, et al., 2021; Zhao et al., 2022).

The regionally varying future trajectories of anthropogenic emissions in the ssp370 scenario (ssp370SST − pdEmis; Figure S4 in Supporting Information S1) results in a different regional response of surface $PM_{2.5}$ concentrations, with the largest increase of 18% across South Asia by 2050. However, by 2095 there are smaller increases across South Asia (6%) and a general decrease in anthropogenic aerosol emissions across other regions resulting in decreases of 4% globally, and 30% across East Asia, Europe, North America, and parts of sub-Saharan Africa. Contrary to this, aerosol emissions and $PM_{2.5}$ concentrations across Western Africa and South America continue to increase by up to 9% in 2095.

Future land-use change (ssp126Lu) results in little significant impacts on annual mean surface $PM_{2.5}$ concentrations in 2050, but by 2095 there is a small 2% increase globally (Figure 3). Regionally, increases in annual mean surface $PM_{2.5}$ concentrations by 2095 occurred across Central Asia (27%), South Asia (7%), southern Africa (7%), and the Middle East (6%), driven by an increase in fine dust aerosol concentrations (Figure S14 in Supporting Information S1) from an increased fraction of bare soil (Figure S15 in Supporting Information S1). This counterintuitive change could be in part due to the inconsistencies from using prescribed land-use changes of ssp126 with the large climate signal of ssp370. Across parts of southern Africa, South America, and north-east United States, there are increases in tree cover (Figure S8 in Supporting Information S1), which result in an increase in BVOC emissions, particularly monoterpenes (Figure S16 in Supporting Information S1), and OAs across these regions (Figure S17 in Supporting Information S1), leading to the increase in annual mean $PM_{2.5}$ concentrations (Figure 3).

3.2. Effective Radiative Forcing

The impact on climate forcing has been calculated in terms of the global annual mean (averaged over 10 years) ERF for each sensitivity scenario in the near-term (centered on 2050) and end of the century (centered on 2095), relative to ssp370SST (Figure 4). However, when calculating the ERF due to transient changes in anthropogenic emissions (including CH_4) the top of atmosphere radiative balance for ssp370SST is taken relative to pdEmis. It is not possible to calculate a global ERF between the ssp370SST reference scenario and the future climate change scenario (pdSST) (see Section 2) and as such this scenario is excluded from further analysis.

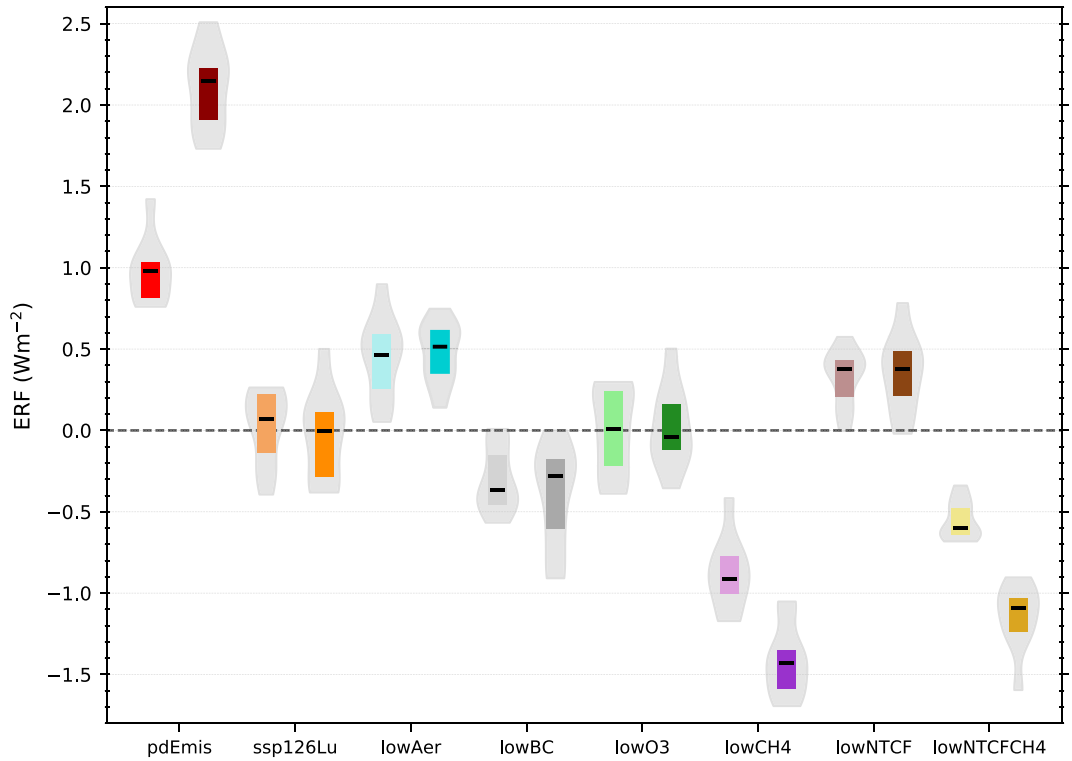

Figure 4. Annual global mean effective radiative forcing (ERF) calculated from UKESM1 in each sensitivity scenario, relative to ssp370SST, apart from for changes in transient anthropogenic emissions which are calculated as ssp370SST relative to pdEmis. The gray shading represents the whole 10-year of global mean ERFs, shown as the density distribution of the data, centered on 2050 (left column) and 2095 (right column) for each scenario. The black line shows the median ERF for each 10-year period, with the box representing the 25th and 75th percentile values of each 10-year distribution.

The sensitivity scenarios that involve future mitigation of non-CH_4 ozone precursor emissions (lowO_3) and different future land-use (ssp126Lu) have a negligible impact on future global climate forcing as the global ERF from changes in NTCFs is centered at about zero in both time periods. The increasingly positive ERF (2.1 ± 0.26 W m^{-2} by 2095) calculated for the pdEmis (anthropogenic emissions only) scenario is driven by the large increase in global CH_4 concentrations in the ssp370 pathway. It also includes a smaller contribution from increases in Nitrous Oxide (N_2O) and an overall positive ERF from the future global reductions in all anthropogenic precursor emissions (CO, NO_x, non-CH_4 VOCs, BC, SO_2, and OAs).

The experiments mitigating individual NTCFs show the balance between the warming and cooling response. Reducing only BC emissions (lowBC) produces a negative ERF that is approximately −0.4 W m^{-2} in both 2050 and 2095, although this might be slightly overestimated due to the strong cloud adjustments to BC absorption in UKESM1 (B. T. Johnson et al., 2019; O'Connor et al., 2021). The BC ERF is regionally concentrated over the Middle East, South and East Asia, corresponding with the large present-day emission source regions (Figure S18 in Supporting Information S1), with any climate response to this forcing potentially being both local and remote (L. Liu et al., 2018). However, a positive global mean ERF is calculated from the reduction in all aerosols and aerosol precursor emissions (lowAer) of approximately 0.5 W m^{-2} in both 2050 and 2095, indicating that at global scale, the reduction in cooling aerosols (mainly from SO_2) outweigh those from warming aerosols (mainly BC). However, the ERF from the reduction of aerosols precursor emissions will be slightly underestimated due to the absence of the small additional radiative effect from nitrate aerosols (Bellouin et al., 2011; Naik et al., 2021). The aerosol ERF is also not uniformly distributed globally, with positive values mainly over the northern mid-latitudes (both land and ocean), and near neutral or negative values over regions with large sources of BC (Figure S18 in Supporting Information S1). This also means that any climate response to these changes in aerosols is also likely to be regionally different.

When combining the reduction in aerosols with non-CH_4 O_3 precursors (lowNTCF) a slightly smaller global ERF is calculated, which agrees well with the CMIP6 multi-model mean of the same scenario (Allen et al., 2021). An increasingly large negative ERF is calculated for reductions in global CH_4 concentrations of -1.42 ± 0.22 W m^{-2} in 2095, which is larger in UKESM1 than other CMIP6 models, mainly due to differing tropospheric rapid adjustments (Allen et al., 2021; O'Connor et al., 2021; Thornhill, Collins, Kramer, et al., 2021). In contrast to the spatial pattern of aerosol ERF, the longer-lived nature of CH_4 results in an ERF (and any climate impact) that is much more evenly distributed across the globe (Figure S18 in Supporting Information S1). Simultaneously mitigating all NTCFs together yields a global ERF of -1.14 ± 0.20 W m^{-2} in 2095, which is again larger than the CMIP6 multi-model mean of the same scenario due to larger contributions from CH_4 forcing in UKESM1 (Allen et al., 2021). The results from Allen et al. (2020, 2021) also highlight the regional disparity in climate response from mitigating aerosol emissions, with significant warming over the Arctic, East Asia, and South Asia. However, the additional inclusion of methane mitigation effectively offsets any warming response from aerosols across these regions, particularly by the end of the century. It is also noted that the global ERF from the individual mitigation scenarios (lowO_3, lowAer, and lowCH_4) do not linearly approximate that from the single combined mitigation experiment (lowNTCFCH$_4$), mainly because of the non-linearity of aerosol processes and interactions, particularly with clouds, that occurs when aerosols are changed in combination with other NTCFs (O'Connor et al., 2021).

4. Climate and Air Quality Co-Benefits

For each of the AerChemMIP sensitivity scenarios, we now provide a quantification of the combined impact on global surface air quality and climate, highlighting the potential for co-benefits (Figure 5 and Table S5 in Supporting Information S1). To make the impact on surface air quality more relevant to the level of human exposure, the Maximum Daily 8-hr Average (MDA8) surface O_3 concentrations and annual mean $PM_{2.5}$ concentrations are compared to the 2005 WHO Air Quality Guideline Values (AQGVs - 100 μg m^{-3} for MDA8 O_3 and 10 μg m^{-3} for $PM_{2.5}$). An additional comparison has been made to the new 2021 WHO AQGV for annual mean $PM_{2.5}$ of 5 μg m^{-3} (Table S5 in Supporting Information S1), but not for O_3 as the updated AQGV remains unchanged. The number of exceedances of the WHO AQGV is computed for each pollutant in each scenario and the change in exceedance is calculated between each scenario and ssp370SST. The future climate change impact scenario (pdSST) is not considered in Figure 5 because it is not possible to calculate a global ERF (see Section 3.2), although this scenario already includes future increases in surface temperature by design.

Figure 5 shows that air quality (both O_3 and $PM_{2.5}$) and climate co-benefits are achieved by simultaneously implementing strong mitigation measures to precursor emissions of both aerosols and tropospheric O_3, including CH_4 (lowNTCFCH$_4$). In this scenario, global climate forcing is -1.1 Wm^{-2} and the number of exceedances of WHO AQGVs are reduced by more than 20% in 2095. The benefit to climate from this mitigation scenario is further highlighted in Allen et al. (2021), where a reduced rate of surface temperature warming is shown across all regions. In contrast, considering only the transient changes in anthropogenic NTCF emissions and global CH_4 concentrations associated with ssp370 (pdEmis) results in detrimental impacts on both climate and O_3 air quality (>15%), with only a small benefit to global $PM_{2.5}$ air quality by 2095 (<10%). This difference in future trajectories of the anthropogenic NTCF emission pathways highlights the penalties for inaction and potential benefits that can be achieved from future policy intervention and strong mitigation measures applied to NTCFs; a reduced rate of climate warming that coincides with benefits to surface air quality and human health.

By conducting a large number of additional sensitivity scenarios with UKESM1, we are also able to quantify the air quality and climate co-benefits from mitigating individual NTCFs and assess the linearity of the benefits from combining NCTF mitigation. The mitigation of global CH_4 concentrations has been recently highlighted as an important measure in achieving a reduced rate of global warming in the near-term, as well as having benefits to O_3 air quality (Abernethy et al., 2021; Allen et al., 2021; Staniaszek et al., 2022). Here we provide further evidence by using AerChemMIP simulations to show that large CH_4 reductions (lowCH_4) benefit future climate forcing (both short and long term) and O_3 air quality (>30%). Furthermore, excluding CH_4 reductions from the combined NTCF mitigation experiment (lowNCTF), results in a detrimental impact on climate, although the benefit to global surface air quality (both O_3 and $PM_{2.5}$) is maintained with the number of exceedances of the WHO AQGVs reduced by >20%. The detrimental impact on climate results from the mitigation of aerosols and aerosol precursor emissions (lowAer), which is particularly strong in the near-term (2050) but still results in benefits to

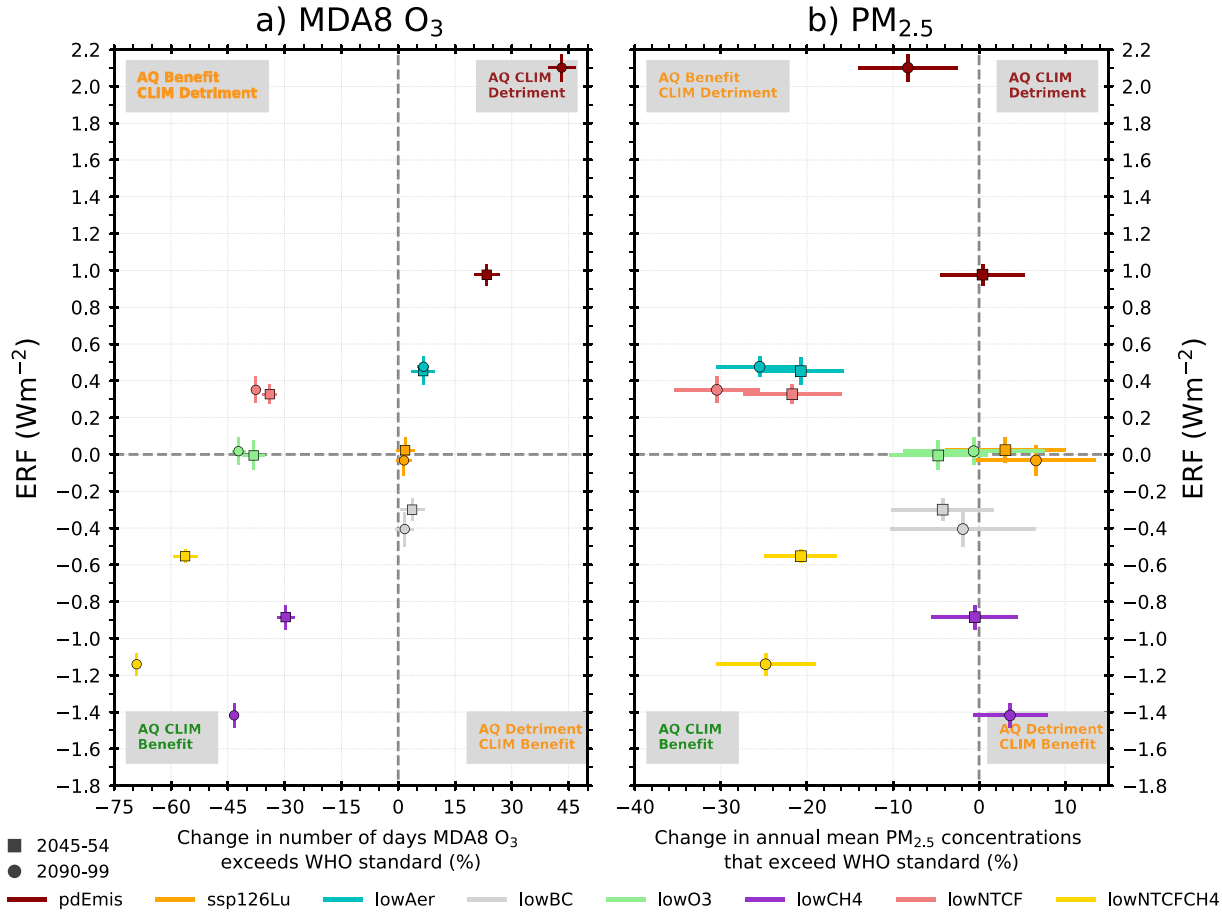

Figure 5. Annual mean global effective radiative forcing (ERF) from UKESM1 in each sensitivity scenario, relative to ssp370SST, compared to (a) the percentage change between each sensitivity scenario and ssp370SST in the number of days globally that the maximum daily 8-hr mean surface (MDA8) O_3 exceeds the WHO air quality guideline value, and (b) the percentage change between each sensitivity scenario and ssp370SST in the number of times globally that the annual mean $PM_{2.5}$ exceeds the 2005 WHO air quality guideline value (corresponding values for comparison to the 2021 WHO air quality guideline value are in Table S5 in Supporting Information S1). Each point represents a 10-year mean value centered on 2050 (square) and 2095 (circle) with the error bars representing 1 × standard error for the ERF and 1 × standard deviation for the pollutant values of these means.

$PM_{2.5}$ air quality (>20%). However, an unintended consequence is that reducing aerosols also slightly worsens O_3 air quality (>5%) due to changes in heterogeneous chemistry (Figure 2). Reducing only BC emissions (lowBC), achieves co-benefits to both air quality and climate, with a particularly strong regional response. The mitigation of aerosols (in terms of timing, components, and regional impact, particularly on other NTCFs) needs careful consideration in future policy measures when attempting to achieve co-benefits to both regional air quality and climate. Solely reducing non-CH_4 tropospheric O_3 precursor emissions (lowO_3) provides benefits to O_3 air quality (40%) with a negligible impact on future climate. Figure 5 also shows that the air quality and climate impacts from the individual mitigation scenarios are not linearly additive, especially on a regional basis (Section 3), when compared to the combined NTCF mitigation scenario. This highlights that there are important non-linearities and interactions between NTCFs when they are reduced in combination, compared to individually (e.g., aerosols, clouds, chemistry and oxidants). This could alter the intended impact of the mitigation policy, particularly at a regional level, requiring further investigation and consideration when policies are being created.

The additional sensitivity scenarios considering only changes in climate and land-use allows for the quantification of impacts from these processes. The future climate change scenario already increases global surface temperatures and results in detrimental impacts on continental surface air quality (Figures 2 and 3). Future land-use policies (ssp126Lu) have a negligible impact on climate (in terms of global ERF) but are slightly detrimental to global surface air quality (increasing both O_3, 2% and $PM_{2.5}$, 7% by 2095). Therefore feedbacks on NTCFs

from such Earth system changes can impact climate and air quality and will also be an important component to consider as part of any future mitigation strategy (Martin et al., 2015; Wang et al., 2020; Zanis et al., 2022).

The more stringent 2021 WHO AQGVs mean that in all future mitigation scenarios, there is a smaller benefit to $PM_{2.5}$ (Table S5 in Supporting Information S1). This implies that mitigation measures will need to go further in the future than those considered here to continue to achieve the largest benefits to air quality and health. Additionally, it should be noted that the impact on $PM_{2.5}$ air quality from all sensitivity scenarios has larger error bars associated with them than for O_3. This reflects the large regional variability in the future response of aerosols, particularly those with natural sources (sea salt and dust), as discussed in Section 3.1 and Figures 2 and 3. Therefore the magnitude of the impact on air quality (benefits or detriments) will also have a large regional variability. For example, the impact from future transient anthropogenic emissions (ssp370SST − pdEmis) shows large regional changes in annual mean $PM_{2.5}$ concentrations (Figure 3), depending on the emission trajectory of each region, which is also reflected in the change in exceedance of WHO AQGVs and thus the large error bars on Figure 5b.

5. Conclusions

Mitigation of NTCFs can have important impacts on climate, influencing the rate of the near-term global surface warming, and also on regional air quality, with consequences for human health. Here we have used output from an extensive range of different future sensitivity studies conducted by UKESM1 as part of the Aerosol and Chemistry Model Intercomparison Project (AerChemMIP) to quantify the impact and co-benefits of different measures on future air quality and climate. Using a single model allows for the impact from NTCFs in a large range of scenarios to be considered at the same time. In addition, the separate impacts from future mitigation of NTCF precursors emissions, both individually and in combination, as well as the impact from future land-use change policies and climate change have been quantified. However, using a single chemistry climate model means that we are not able to fully account for the range of possible future projections in both air quality and climate, as shown in multi-model studies (Allen et al., 2021; Turnock et al., 2020). This assessment highlights the mitigation measures which benefit both air quality and climate, and the drivers of these changes, which could help inform future policy. We show that co-benefits to future air quality and climate can only be achieved from simultaneous, strong mitigation of all NTCF emission sources. If such mitigation measures are not enacted, then there are potential penalties to both climate and regional air quality. If global CH_4 concentrations are not mitigated, then a detrimental impact to climate occurs and the benefits to air quality are reduced. If only aerosols and their precursor emissions are mitigated, then there are detrimental impacts on both O_3 air quality (driven by chemical interactions) and climate, although there are still benefits to $PM_{2.5}$ air quality. However, targeting certain aerosol components, for example, BC, can provide co-benefits to both air quality and climate, particularly at the regional scale. Nevertheless, it is noted that stronger future mitigation measures will be required than those presented here to enable more parts of the world to achieve the more stringent 2021 WHO air quality guideline values, enabling better air quality and improvements to human health. Comparing the different impacts on climate forcing and air quality due to combined NTCF mitigation with those when NTCFs are individually reduced, highlights that there are important non-linearities and interactions between NTCFs (e.g., aerosols and clouds) that need to be considered further. Future changes in climate and land-use are shown to alter regional NTCFs, via different mechanisms, and also have an impact on climate forcing and regional air quality. It is essential to consider the NTCF response to these Earth system changes alongside any measures to mitigate anthropogenic emissions. The interaction and response of NTCFs to potential future changes are important issues that need to be considered when designing future mitigation measures that seek to benefit both air quality and climate.

Data Availability Statement

CMIP6 data is archived 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 is 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. 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.

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