The impact of climate mitigation measures on near term climate forcers

Environmental Research Letters

LETTER

The impact of climate mitigation measures on near term climate forcers

S T Turnock[1,3], S Smith[2] and F M O'Connor[1]

[1] Met Office Hadley Centre, Fitzroy Road, Exeter, Devon, United Kingdom
[2] Joint Global Change research Institute, Pacific Northwest National Laboratory, College Park, MD 20740, United States of America
[3] Author to whom correspondence should be addressed.

E-mail: steven.turnock@metoffice.gov.uk

Keywords: climate, air quality, co-benefits, aerosols, air pollutants, mitigation

Supplementary material for this article is available online

OPEN ACCESS

RECEIVED
9 April 2019

REVISED
20 August 2019

ACCEPTED FOR PUBLICATION
6 September 2019

PUBLISHED
15 October 2019

Abstract

Here we quantify the regional co-benefits to future air quality on annual to daily mean timescales from implementing mitigation measures to stabilise future climate. Two consistent future emissions pathways are used within the composition-climate model HadGEM3-UKCA: one is a reference pathway of future economic growth and development (REF), whilst the Representative Concentration Pathway 4.5 (RCP4.5) assumes the same development pathway but stabilises anthropogenic radiative forcing at 4.5 W m^{-2} in 2100. Implementing greenhouse gas (GHG) mitigation measures in RCP4.5 reduces global mean air pollutant emissions by up to 30% in the 2050s, in addition to mitigating climate. Annual mean surface concentrations of ozone and $PM_{2.5}$ decrease by 10%–20% from the combined reductions in emissions and climate change. The number of days exceeding the World Health Organization's (WHO) daily mean air quality standards are reduced by up 47 days for ozone and 15 days for $PM_{2.5}$ over different world regions. The air quality co-benefits from mitigation measures are mainly achieved from reductions in anthropogenic emissions, although benefits can be offset due to changes in climate. In terms of anthropogenic climate forcing, while the reduction in global mean effective radiative forcing (ERF) in 2050, relative to the 2000s, due to enacting carbon dioxide mitigation measures (−0.43 W m^{-2}) is enhanced by decreases in tropospheric ozone (−0.26 W m^{-2}) and methane (−0.2 W m^{-2}), it is partially offset by a positive aerosol ERF from reductions in aerosols (+0.35 W m^{-2}). This study demonstrates that policies to mitigate climate change have added co-benefits for global and regional air quality on annual to daily timescales. Furthermore, the effectiveness of the GHG policies in reducing anthropogenic climate forcing is enhanced in the near-term by reductions in ozone and methane despite the increased forcing due to reductions in aerosols.

1. Introduction

The air pollutants ozone (O_3) and particulate matter (PM) can have a detrimental impact on human health (Lelieveld *et al* 2015) and variable impacts on ecosystems (Fowler *et al* 2009). Additionally, both pollutants are 'Near Term Climate Forcers' (NTCFs) because they influence climate in the short-term (due to their short atmospheric lifetime) by perturbing the Earth's radiative balance (Myhre *et al* 2013). O_3 acts as a greenhouse gas (GHG) whereas PM both scatters and absorbs radiation (aerosol radiation interactions—ari), in addition to altering the microphysical properties of clouds (aerosol cloud interactions—aci). Changes to climate (via meteorological parameters) can also affect the spatial distribution and concentrations of air pollutants (von Schneidemesser *et al* 2015, Doherty *et al* 2017, Silva *et al* 2017).

Future mitigation measures targeted at reducing air pollutant emissions are generally enacted to improve local air quality and benefit human health (US EPA 2011, Turnock *et al* 2016). However, policies

focussed on the mitigation of climate, through the reduction of GHGs, can also inadvertently impact the concentration and spatial distribution of air pollutants in the atmosphere (von Schneidemesser *et al* 2015). This can occur through changes in the rate of air pollutants co-emitted from carbon sources and by changes in the physical climate. The effect of future changes in climate on PM is uncertain (Jacob and Winner 2009, Allen *et al* 2016) but climate change is generally considered to decrease background O_3 concentrations (Isaksen *et al* 2009, Fiore *et al* 2012) and worsen surface O_3 in polluted regions—the so-called 'climate penalty' (Rasmussen *et al* 2013, Colette *et al* 2015). The number of premature mortalities associated with exposure to $PM_{2.5}$ (particles with a diameter less than 2.5 micrometres) and O_3 is likely to increase under future climate change (Doherty *et al* 2017, Silva *et al* 2017). Less stringent climate mitigation measures, leading to a larger temperature response, could also eliminate any future benefits to surface O_3 from reductions in precursor emissions (Fortems-Cheiney *et al* 2017). It is therefore important to consider the impact from air quality and climate mitigation measures together as future air quality will be determined by the combined effect of both.

Model studies using the Representative Concentration Pathways (RCPs) in the 5th Coupled Model Intercomparison Project (CMIP5) simulated both positive and negative changes to surface O_3 and PM concentrations in the 2050s, relative to the 2000s, from the combined effects of changes in emissions and climate (Kirtman *et al* 2013, Young *et al* 2013, Kim *et al* 2015, Glotfelty and Zhang 2017). For O_3, reductions in global mean surface concentrations are simulated in the 2050s for all RCPs apart from RCP8.5 whereas, global mean $PM_{2.5}$ concentrations are predicted to decrease in all scenarios. Reductions in surface O_3 and $PM_{2.5}$ concentrations of up to 20% in 2050 were simulated over Europe, Asia and North America using future climate mitigation measures targeting mainly methane (CH_4) and black carbon (BC) sources (Stohl *et al* 2015). However, there is a large range of regional responses (positive and negative) in O_3 and PM, both within models and to the different future pathways, highlighting the large uncertainty in future estimates (Fiore *et al* 2012). Changes to future $PM_{2.5}$ concentrations tend to be smaller than for O_3 due to the larger contributions from natural sources (e.g. dust, sea-salt emissions), that are inherently more variable due to the assumed future climate state.

Solely implementing climate mitigation policies has been shown to improve future air quality and human health at a carbon price that is less than air pollution abatement costs (Shindell *et al* 2012, West *et al* 2013, Vandyck *et al* 2018). Results from multiple Integrated Assessment Models (IAMs) on the co-benefits of climate policies for air quality found a benefit to crop yields and a reduction in global exposure to $PM_{2.5}$ above World Health Organization (WHO) values in 2050, but with large variations over India and Africa (Rao *et al* 2016, Vandyck *et al* 2018). Combining climate and air quality mitigation measures results in 39% of the global population in 2050 being exposed to $PM_{2.5}$ concentrations less than the WHO annual guideline value of 10 $\mu g\ m^{-3}$ (Rao *et al* 2016). Applying carbon dioxide (CO_2) mitigation measures over the USA in the 2050s reduces surface concentrations of O_3 and $PM_{2.5}$ and causes a negative O_3 and positive aerosol radiative forcing (Lee *et al* 2016, Zhang *et al* 2016). Over Europe, implementing climate policies provides cost savings from reduced health impacts in 2050 due to reductions in both $PM_{2.5}$ (mainly emission driven changes) and O_3, although the sign of the O_3 response depends on the magnitude of future climate change (Schucht *et al* 2015). Over China, simulating an illustrative climate policy for peaking CO_2 emissions in 2030 reduces annual mean $PM_{2.5}$ concentrations by up to 12%, with 94 000 associated avoided premature mortalities and associated co-benefits that are larger than mitigation costs (Li *et al* 2018). Air quality co-benefits for health and crop yields could be larger if the ambitious long-term goals of the Paris Agreement on climate change are met (Reis *et al* 2018, Vandyck *et al* 2018). These studies highlight the potential co-benefits to air quality and human health that can be achieved from solely implementing climate mitigation measures.

It is important to further understand the impact from climate mitigation measures on air pollutants, as uncertainties still exist in the future impact on air quality and climate, especially the extent to which they could alter the efficacy of air quality mitigation measures. Previous studies have tended to only focus on the air quality and health co-benefits, whereas here we systematically assess the impact of climate mitigation measures on regional air pollutants (O_3 and $PM_{2.5}$) across different timescales (annual, seasonal, daily) and on near-term climate forcing. In this study we use a set of self-consistent future climate scenarios (RCPs used in CMIP5), in a similar way to West *et al* (2013), but within a fully coupled global composition-climate model (HadGEM3-UKCA). Here we perform a systematic assessment of the impact on air pollutants (O_3 and $PM_{2.5}$) from climate mitigation measures across specific world regions on daily, seasonal and annual timescales, to assess the exposure of the world's population to concentrations above WHO guideline values. The influence from the reduction in co-emitted sources and climate change are quantified separately by using additional sensitivity simulations. By analysing 30 years of global climate simulations, that include interactive chemistry and aerosols coupled to climate, we are able to more fully consider the effect of climate variability on the future projection of air pollutants (Garcia-Menendez *et al* 2017, Shen *et al* 2017). This is particularly important for Earth system feedbacks, which can be strongly affected by different future climate states (e.g. changes to natural emission sources of aerosols, and have not been

previously considered in this context). We also quantify for the first time the additional climate co-benefit from reducing carbon emissions on the change in effective radiative forcing (ERF) from the near-term climate forcers relevant to air quality; O_3, CH_4, BC and total PM.

2. Methods

2.1. Emission scenarios

Future pathways of socio-economic development, including changes to air pollutant emissions and GHGs, previously used in CMIP5 are also used here to study the impact of climate mitigation measures on air quality and climate forcing. Decadal mean air pollutant emissions and GHG concentrations centred on the year 2000 (Lamarque *et al* 2010) are used within a baseline scenario for model evaluation purposes (BASE 2000). Consistent future GHG concentration and air pollutant emission pathways developed by the same IAM are used to assess impacts in the 2050s. Like in West *et al* (2013), we compare RCP4.5, developed by the Global Change Assessment Model (Thomson *et al* 2011), to its associated reference pathway (REF). See section S1 available online at stacks.iop.org/ERL/14/104013/mmedia for supplementary scenario details.

The air pollution emission controls assumed in REF are the same as in RCP4.5, allowing any differences in emissions to be attributable to the climate mitigation policies within RCP4.5. The magnitude of change in carbon emissions in 2050 between RCP4.5 and REF is a mid-range climate policy scenario, intermediate between the Nationally Determined Contributions and reductions required to meet the 2 °C goal set out in the Paris Agreement. The REF to RCP4.5 change in SO_2 and NO_X, key drivers of air pollution, is also of intermediate magnitude when compared to changes amongst the shared socio-economic pathways (SSPs) used in CMIP6 between the reference and 4.5 W m^{-2} scenarios (Rao *et al* 2017). Whereas, changes in other air pollutants (CO, NMVOCs, BC and OC) between RCP4.5 to REF are larger than in the SSPs (figure S1). Figure 1 and table S1 show that implementing climate mitigation measures, the difference between RCP4.5 and REF (referred to as RCP4.5 2050 and REF 2050), has a relatively large impact on regional air pollutant emissions in 2050. A global reduction in air pollutant emissions of up to 30% in the 2050s results from solely implementing the climate mitigation measures within RCP4.5, with larger regional reductions. Carbon monoxide (CO) and BC emissions are reduced by more than 50% over North America and Russia, attributed to a reduction in biomass burning of the boreal forest. For some species (e.g. NOx, SO_2), the reduction in air pollutant emissions over Europe and North America from solely implementing climate mitigation measures in the 2050s, tends to be smaller than that from combined air pollution controls and climate policies over the period 2000 to 2050 (RCP4.5 2050—BASE 2000). However, over the rapidly developing regions of Africa and South Asia, implementing climate mitigation measures could offset some of the anticipated increase in air pollutant emissions e.g. SO_2.

2.2. Model set up

In this study, an atmosphere only configuration of the fully coupled HadGEM3-UKCA composition climate model (see section S2 of the supplementary for details) was used at a horizontal resolution of 1.875° by 1.275° (~140 km at mid latitudes) and 85 vertical levels (up to 85 km). Timeslice simulations were conducted where the climate in each scenario is represented by using decadal mean prescribed sea ice (SI) distributions, sea surface temperatures (SSTs), concentrations of well-mixed GHGs and ozone depleting substances centred on the year 2000 in BASE 2000 and centred on 2050 in RCP4.5 and REF. SI and SST distributions for RCP8.5 simulations (Jones *et al* 2011) from HadGEM2-ES (Collins *et al* 2011) are used to represent the climate in REF, as no future climate simulations have been performed in any model for this pathway. Tables 1 and S2 summarise all simulations performed in this study, which have been conducted for a 30 year averaging period to more fully account for the influence of climate variability.

The difference between the RCP4.5 2050 and REF 2050 simulations will show the impact on future air quality from undertaking mitigation measures to stabilise climate. The magnitude of the reduction in carbon emissions and changes in air pollutants considered here in 2050 are from a mid-range climate policy scenario (figure S1), meaning that the overall air quality co-benefits will be intermediate. A student t-test has been performed to assess whether the difference is significant at the 95% confidence interval. To isolate the influence of changes in climate versus that from co-emission sources, a simulation (REF4.5 2050) is conducted which uses the model setup in REF 2050 but with the SI and SSTs replaced by those used in RCP4.5 2050. Further experiments have been undertaken to calculate the ERF, as defined in Forster *et al* (2016), for CO_2, CH_4, O_3, BC and total aerosols (PM) between the 2000s and 2050s for both RCP4.5 2050 and REF 2050 (table S2).

2.3. Model evaluation

The BASE 2000 model simulation has been evaluated against surface observations for $PM_{2.5}$ and O_3 (see section S3 of supplementary for details). Surface $PM_{2.5}$ concentrations have been obtained for all the locations currently compiled within the Global Aerosol Synthesis and Science Project (GASSP) database (http://gassp.org.uk/data/; Reddington *et al* 2017). Surface O_3 observations have been obtained from the Tropospheric Ozone Assessment Report database (Schultz *et al* 2017). An evaluation is performed for annual,

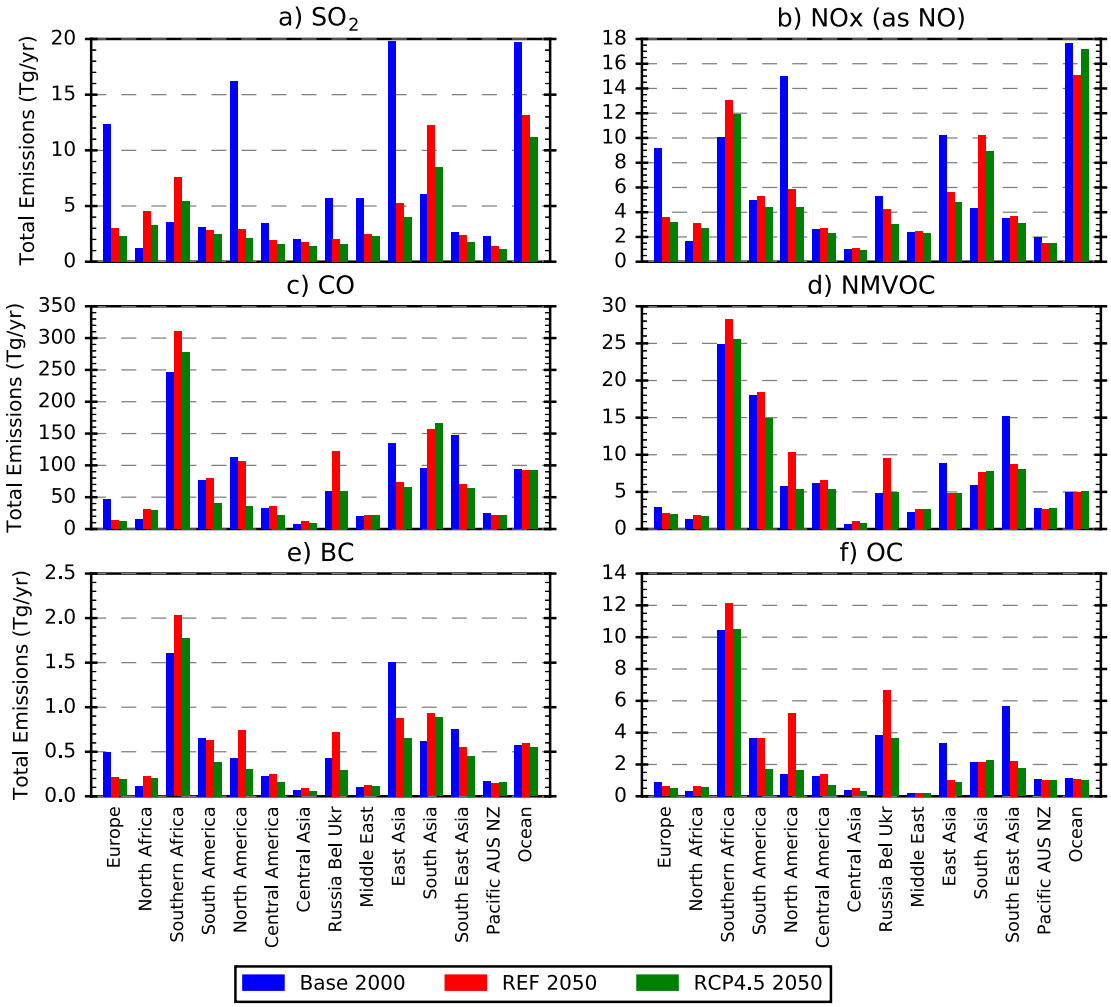

Figure 1. Annual regional total anthropogenic, shipping and biomass burning emissions of (a) sulphur dioxide (SO_2), (b) nitrogen oxide(s) (NOx, represented as NO), (c) carbon monoxide (CO), (d) non-methane volatile organic compounds (NMVOCs), (e) black carbon (BC) and (f) organic carbon (OC) for the BASE 2000, RCP4.5 2050 and REF 2050. Regions are defined in figure S2. Units are in mass of emitted species per year, apart from (d) to (f) where it is Tg C yr^{-1}.

Table 1. Details of timeslice model simulations conducted in this study for a 30 year averaging period, with an additional 10 years of spin up (see table S2 for details of experiments to quantify effective radiative forcing).

Simulation	Time period	Air pollutant emissions	SST/Sea Ice
BASE 2000	2000s	All from historical dataset in 2000	2000s
RCP4.5 2050	2050s	All from RCP4.5 for 2050	RCP4.5
REF 2050	2050s	All from REF for 2050	RCP8.5
REF4.5 2050	2050s	All from REF for 2050	RCP4.5

seasonal and daily mean timescales (daily for O_3 is the monthly mean of the daily maximum 8 h mean value). Due to the limited amount of observed $PM_{2.5}$ data available before 2000, measurement data is based on a decadal mean over the 2000–2010 period for both $PM_{2.5}$ and O_3 to provide a consistent comparison to the BASE 2000 simulation.

A summary of the surface O_3 and $PM_{2.5}$ model evaluation, in terms of the spread in normalised mean bias factors at observation sites, is shown in figure 2 for different timescales (annual, seasonal and daily) and across different regions. The model slightly overpredicts annual mean surface O_3 concentrations in the northern hemisphere (by a factor of 1–1.5) and underpredicts southern hemisphere concentrations (by a factor of ~1.5), in a similar way to other global models (Young *et al* 2018). Seasonally, the model underestimates wintertime and overestimates summertime surface O_3 measurements. Figure 2 shows that HadGEM3-UKCA generally underpredicts annual mean surface $PM_{2.5}$ concentrations, with a better representation of observed summertime values and a consistent low model bias in wintertime. The model observational biases for surface $PM_{2.5}$ are similar to those identified before (Turnock *et al* 2015) and in other global and regional models (Glotfelty *et al* 2017,

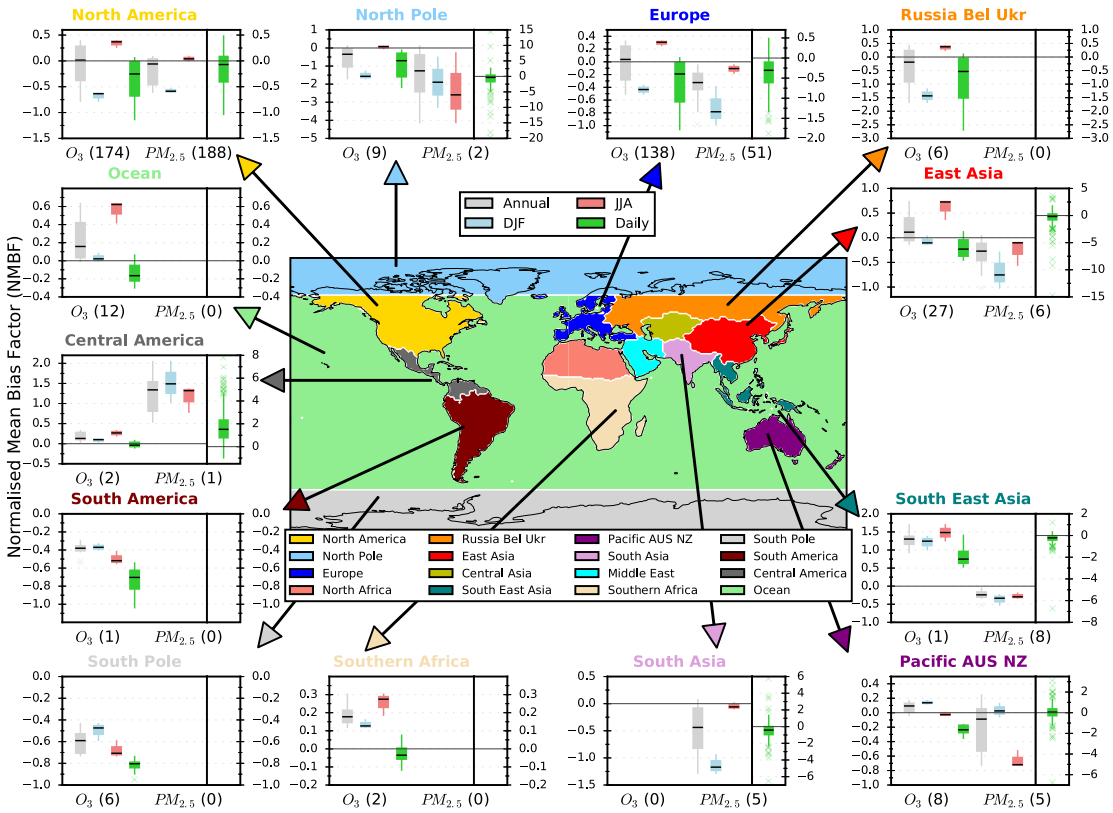

Figure 2. Normalised mean bias factors (NMBF) calculated by comparing modelled concentrations of surface O_3 and $PM_{2.5}$ in BASE 2000 to observations across each region. The solid line shows the median value, the boxes show the 25th and 75th percentile values with the error bars showing the maximum and minimum values and the crosses representing outliers (values >1.5× interquartile range). The total number of observations used is shown in brackets. Comparisons on annual (grey), summertime (red), wintertime (blue) and daily (green) timescales are shown. NMBFs for daily mean $PM_{2.5}$ concentrations are shown on a separate axis on the right of each graph.

Solazzo *et al* 2017, Im *et al* 2018). For both O_3 and $PM_{2.5}$, the model under-represents the elevated daily surface concentrations during pollution episodes, which is expected when using a global model driven by decadal mean monthly emissions at a horizontal resolution of >100 km. The magnitude of seasonal concentrations and similar daily events in the future will also be underestimated by the model, although the simulated change between future scenarios will be consistent, but conservative in magnitude.

3. Results and discussion

3.1. Regional impact on air quality

Implementing climate mitigation measures (RCP4.5 2050 minus REF 2050) reduces annual mean surface O_3 concentrations across continental areas by up to 2 ppbv (table S3), with maximum reductions over northern hemisphere mid-latitudes in June, July, and August (JJA) (figure 3). Annual mean surface $PM_{2.5}$ concentrations reduce over Asia (Central, South and East) by up to 2.5 $\mu g\ m^{-3}$, with the largest change in December, January, and February (DJF). The reduction in surface $PM_{2.5}$ tends to be largest over anthropogenic source regions and dominated by changes to sulphate, BC and organic aerosol (figure S3). However, changes in surface $PM_{2.5}$ concentrations are less coherent than for O_3 due to the variable response of natural PM emission sources (dust and sea salt) in different future climatic states (figure S3). Large changes in the outflow from the Saharan dust source region are simulated on both the annual and seasonal timescales, although the changes are not significantly different between RCP4.5 and REF at the 95% confidence level. However, this does indicate the large potential feedback that natural emission sources could have in the future, potentially offsetting benefits from anthropogenic emission reductions.

Implementing climate mitigation measures reduces population weighted surface O_3 concentrations in the 2050s across the majority of regions in most seasons (figure 4). Globally, surface O_3 concentrations reduce in all seasons. A maximum global reduction of 2.2 ppbv occurs in JJA (table S4), which is strongly driven by the reduction of co-emitted tropospheric O_3 precursors (−2.6 ppbv) but partially offset by the effect of climate change (temperature reduction) acting to increase background (i.e. non-episodic) surface O_3 concentrations (+0.4 ppbv) due a reduction water vapour and O_3 loss (table S5). Largest benefits to surface O_3 occur in spring and summer over most northern hemisphere regions. Maximum reductions of up

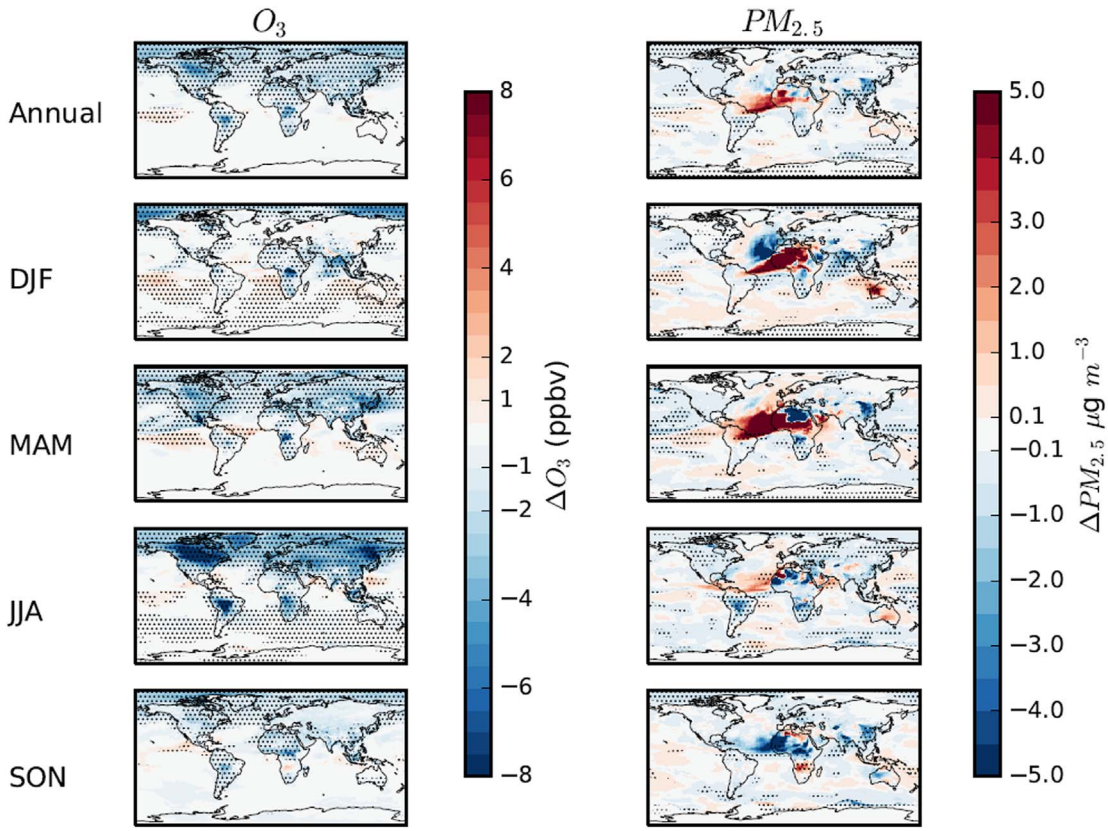

Figure 3. Annual and seasonal mean differences in surface O_3 and $PM_{2.5}$ in the 2050s between RCP4.5 2050 and REF 2050. Seasons are defined as DJF—December, January, February, MAM—March, April, May, JJA—June, July, August, SON—September, October, November. Stippling shows differences that are statistically significant at the 95% confidence interval using a student t-test.

to 3 ppbv occur in JJA over Europe, East Asia and North America, mostly due to the reduction of co-emitted tropospheric O_3 precursors (<-3 ppbv). Changes to climate from mitigation measures tend to increase surface O_3 concentrations over most regions by less than 1 ppbv. Surface O_3 increases by 0.3 ppbv over the Pacific, Australia and New Zealand region in DJF due to changes in climate (+0.4 ppbv) with a slight offset from emission changes (−0.1 ppbv).

Seasonal mean changes in population weighted surface $PM_{2.5}$ concentrations due to implementing climate mitigation measures are smaller and more variable (figure 4). Global mean population weighted $PM_{2.5}$ concentrations decrease by 0.6 –1.2 $\mu g\ m^{-3}$ in most seasons, mainly due to the reduction of sulphate, BC and organic matter from emission changes (figure S3). However there is an increase in global mean population weighted $PM_{2.5}$ concentrations in March, April, and May (MAM: +0.2 $\mu g\ m^{-3}$), which is dominated by changes in dust and organic aerosol sources (figure S3). Climate change mitigation measures act to increase $PM_{2.5}$ (+1.0 $\mu g\ m^{-3}$, figure S5) in MAM, which outweigh benefits from emission reductions (−0.8 $\mu g\ m^{-3}$, figure S4). A large reduction in population weighted surface $PM_{2.5}$ concentrations of >2 $\mu g\ m^{-3}$ occurs over South Asia in DJF from emission reduction measures, primarily from SO_2 decreases (figure 1). Certain regions (Central Asia, Middle East and North Africa) are influenced by natural PM (dust) sources and exhibit a large variability in their $PM_{2.5}$ response. However, the large overlapping error bars on figure 4 and absence of stippling on figures S3–S5 show that these changes in $PM_{2.5}$ near the dust source regions are not significant. Future projections of surface $PM_{2.5}$ concentrations are more variable and harder to attribute to a particular influence, as indicated by the large overlapping error bars from emission and climate drivers.

Overall, implementing GHG mitigation measures reduces global population weighted annual mean surface concentrations of O_3 and $PM_{2.5}$ in 2050 by 1.6 ppbv and 0.5 $\mu g\ m^{-3}$, respectively. Benefits and penalties to regional air pollutants from measures to stabilise climate are shown to vary both regionally and seasonally. The global and regional co-benefits to air quality are smaller in this study for O_3 and $PM_{2.5}$ and have a more variable response for $PM_{2.5}$ than in West *et al* (2013) and Zhang *et al* (2017). The difference between studies can be attributed to the use of a different model and the larger simulated influence of climate change on ozone (globally 15%) and $PM_{2.5}$ (globally 30%). The increase in surface O_3 solely due to the effects of climate change is spatially consistent with that in West *et al* (2013) but slightly larger due to the higher climate sensitivity of the model (HadGEM2; Collins *et al* 2011) used to provide SST and sea ice

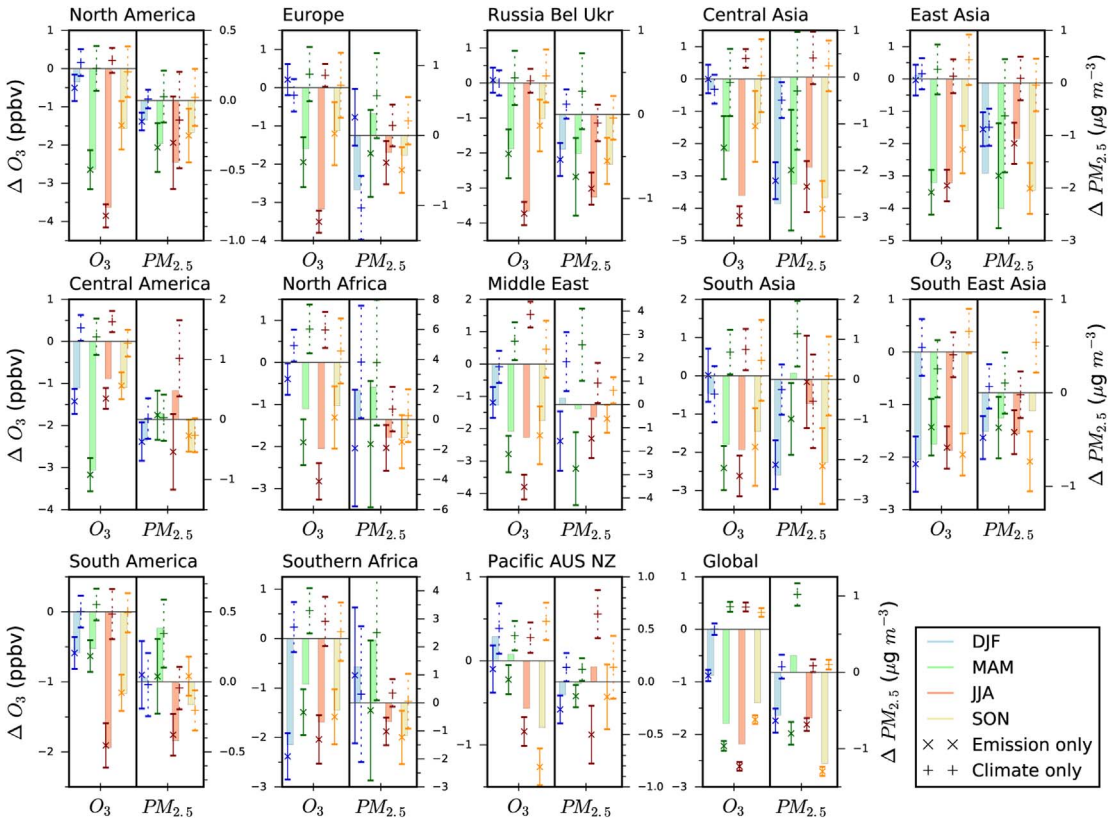

Figure 4. Total seasonal mean difference in population weighted surface O_3 and $PM_{2.5}$ in the 2050s across the different regions from implementing climate mitigation measures (RCP4.5 2050–REF 2050, shown in solid coloured bars). The regional difference due to solely emission related changes (RCP4.5 2050–REF4.5 2050) is shown by the X symbol, whereas that due to changes solely in climate (REF4.5 2050–REF 2050) is shown by + symbol. The error bars on the X and + symbols represent the standard deviation in the mean regional response over the 30 year simulation period.

fields (Andrews *et al* 2012). The influence of climate variability was shown to be particularly important for interactive natural sources of aerosols (dust and sea salt) (figures S4 and S5). It is therefore important to account for climate variability in model simulations where Earth System feedbacks could limit improvements from future anthropogenic emission controls. Nevertheless, the benefits from co-emission reductions outweigh any penalties from mitigating climate and result in a net benefit of climate policies to surface O_3 and $PM_{2.5}$ concentrations, in accordance with West *et al* (2013) and Zhang *et al* (2017).

3.2. Impact on WHO air quality guideline values (AQGVs)

Simulated daily mean surface $PM_{2.5}$ concentrations and the Daily Maximum 8 hour mean (DM8H) surface O_3 concentrations have been compared to the WHO AQGVs, 2005 (25 $\mu g\,m^{-3}$ for $PM_{2.5}$ and 100 $\mu g\,m^{-3}$ for O_3). Solely implementing the RCP4.5 climate mitigation measures reduces the number of days per year in the 2050s that the surface DM8H O_3 exceeds the WHO AQGV (figure 5 and table S6). Largest benefits occur across Asia, Europe and North America where the regional mean exceedance reduces by more than 25 days (table S6). The reductions in the 2050s over these regions are even larger when compared to the number of exceedances in the 2000s. However, for regions like Africa, Middle East and South Asia climate mitigation measures act to limit any future increase in the number of exceedances compared to the 2000s.

Whilst the absolute magnitude of simulated daily mean $PM_{2.5}$ concentrations is underestimated by the model (figure 2), there is a change in the number of daily exceedances due to climate mitigation measures, which is smaller than that for O_3 due to the influence of climate variability on emissions from natural sources (section 3.1). Changes in $PM_{2.5}$ from dust source regions contributes to the small increase in the number of days that daily mean $PM_{2.5}$ exceeds the WHO AQGV over the Central America, South America and Pacific, Australia, New Zealand regions. Across the anthropogenic source regions of East Asia and South Asia, climate mitigation measures reduced the regional mean exceedances of the WHO AQGV by more than 10 days (table S6). Compared to the large number of exceedances in the 2000s, climate measures provide an additional reduction of exceedances for East Asia and limits future increases over South Asia.

In summary, climate mitigation measures provide an additional reduction in the daily exposure of the population to elevated surface concentrations of both O_3 and $PM_{2.5}$, particularly over regions (e.g. South and

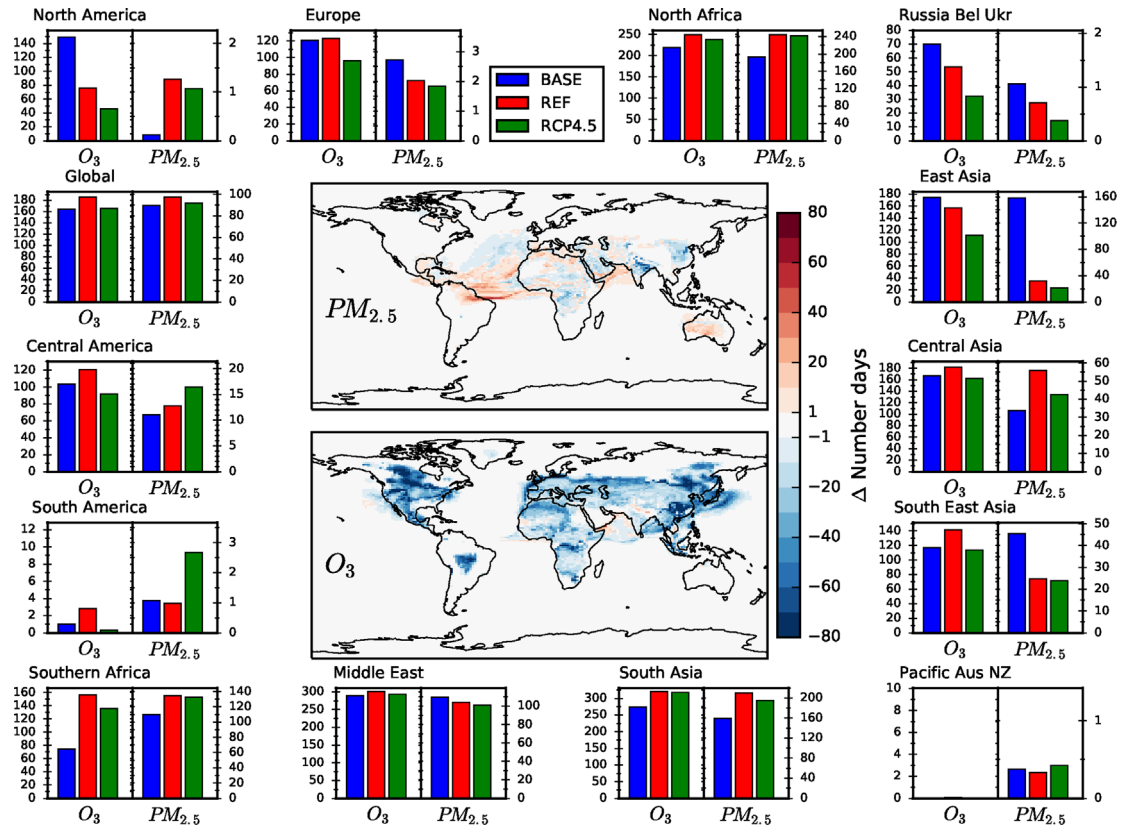

Figure 5. Population weighted mean number of days exceeding the O_3 and $PM_{2.5}$ World Health Organization Air Quality Guideline values (2005) within each region for the 2000s (BASE 2000; blue) and the 2050s for RCP4.5 2050 (green) and REF 2050 (red). Centre maps show the change in the number of exceedance days for O_3 and $PM_{2.5}$ in the 2050s as a result of climate mitigation policies (RCP4.5 2050–REF 2050).

Table 2. Effective radiative forcing (± one standard error) of O_3, aerosols (ari and aci), CH_4 and CO_2 in 2050 relative to 2000 in RCP4.5 and REF. (see table S2 for simulations used to calculated ERFs)

	Effective radiative forcing (ERF) in 2050 relative to 2000 (Wm^{-2})		
Pollutant	RCP 4.5	REF	Difference
Ozone	$+0.04 \pm 0.03$	$+0.30 \pm 0.04$	-0.26
Aerosols (All-Sky)	$+0.97 \pm 0.10$	$+0.63 \pm 0.07$	$+0.35$
Black carbon (All-Sky)	-0.02 ± 0.03	-0.04 ± 0.03	$+0.02$
Methane	-0.02 ± 0.03	$+0.18 \pm 0.03$	-0.20
CO_2	$+1.47 \pm 0.04$	$+1.90 \pm 0.05$	-0.43

East Asia) where there is currently a high population exposure.

3.3. Changes to ERF

As both O_3 and PM are NTCFs, any change in their concentration could have an impact on climate forcing in addition to air quality. Implementing the climate mitigation measures in RCP4.5 not only reduces CO_2 and CH_4 concentrations and their radiative forcing compared to REF but will also inadvertently change O_3 and aerosol (PM) radiative forcing. Table 2 shows the calculated global mean ERFs between 2000 and 2050 for RCP4.5 2050 and REF 2050 using the experiments listed in table S2. A large reduction in global CO_2 ERF by 2050 is shown by implementing climate mitigation measures to stabilise future climate (-0.43 W m^{-2}). Additional reductions in climate forcing result from changes in CH_4 (-0.20 W m^{-2}) and O_3 (-0.26 W m^{-2}, shown by the decrease in O_3 burden from changes in precursor emissions and CH_4, figure S6). However, the reduction in aerosol concentrations by 2050, as shown by the decrease in the column integrated aerosol optical depth (figure S7), results in an increase in the positive aerosol ERF ($+0.35$ Wm^{-2}) from aerosol-radiation and aerosol-cloud interactions. However, it has been shown that the aerosol ERF is quite strong in this version of the model (Mulcahy *et al* 2018) and could overestimate the impact of aerosols on climate. Changes in BC concentrations between the RCP4.5 2050 and REF 2050 scenarios has a negligible impact on the BC ERF. In contrast to the more uniform CO_2 and CH_4 ERF

(figure S8), the aerosol ERF is regionally variable and highlights the effect from changes to different source regions (table S8). Regionally, the largest positive change in aerosol ERF occurs across South and East Asia (figure S8) due to large changes in aerosols, whilst for O_3 the reductions in ERF are largest across Europe. The benefits to climate forcing from reductions in CO_2 and CH_4 ERFs due to climate mitigation measures is enhanced by reductions in the tropospheric O_3 ERF, but partially offset by the positive aerosol ERF from decreases in aerosols.

4. Conclusions

Mitigation measures to stabilise future climate are targeted at reducing emissions of CO_2, its radiative forcing, and future climate change. However, implementing these measures has the potential to have an inadvertent impact on concentrations of air pollutants from changes in future climate, as well as to co-emitted precursors. Here we use a coupled composition-climate model to assess the impact of future climate mitigation measures on air pollutants by using simulations with the same air pollutant controls but different climate policies. Globally, climate policies reduce the co-emission of air pollutants in 2050 by 10%–30%, in addition to stabilising climate at a lower value of global mean surface temperature.

From our simulations we estimate that the implementation of climate mitigation measures reduces surface concentrations of O_3 and $PM_{2.5}$, with annual mean co-benefits of up to 10% regionally. Larger benefits of up to 15% are simulated in summertime for surface O_3 and in wintertime for $PM_{2.5}$ over northern hemisphere anthropogenic source regions. Scenarios used in this study were those used in CMIP5 as newer scenarios, providing a greater number of future trajectories with differing levels or air pollutant and climate mitigation, were not available (Rao *et al* 2017, Gidden *et al* 2019). The extent of climate mitigation considered here in 2050 represents a mid-range climate policy scenario, with air quality co-benefits that are of intermediate magnitude (figure S1). The scenarios used in CMIP6 provide a larger range of future climate and air pollutant emission trajectories, with the potential for larger or smaller air quality co-benefits.

The co-benefit to surface air quality is mainly achieved through the reduction of co-emitted air pollutants and their precursors, in accordance with West *et al* (2013). However, over certain regions, there are small increases in air pollutants in response to the changes in climate induced from climate mitigation measures. Simulated co-benefits of climate mitigation measures to air quality are smaller here than in West *et al* (2013) due to the use of a different model and the larger simulated influence of climate change. This highlights the need for further investigation (through a multi-model assessment) on the importance of Earth System feedbacks in limiting any benefits from future emission controls.

Implementing climate mitigation measures reduces the exposure of the population to daily concentrations of $PM_{2.5}$ and O_3 above the WHO air quality guideline values. For regions currently experiencing high levels of air pollution, such as East and South Asia, there are notable reductions in the number of days that concentrations of $PM_{2.5}$ and O_3 exceed the WHO Air Quality Guideline Values in the 2050s. Climate mitigation measures are therefore able to provide an additional reduction, on top of direct air pollutant controls, in the daily exposure of the population to high levels of air pollutants, with associated co-benefits for human health (e.g. West *et al* 2013).

O_3 and PM, are radiatively active and can influence the Earth's radiative balance as well as impact on surface air quality. Changes to their concentrations from implementing climate mitigation measures alters their radiative effect on climate. Reductions in aerosols (PM) increases their radiative forcing in 2050 (relative to 2000) whilst reductions in O_3 reduce its radiative forcing. Reductions in radiative forcing from CO_2, CH_4 and O_3 due to climate mitigation measures benefits anthropogenic climate forcing, although this is offset by the increased aerosol forcing.

Future implementation of climate mitigation measures results in a co-benefit to both air quality and climate. Surface concentrations of air pollutants are reduced, mainly from decreases in co-emitted precursors, which improves air quality and reduces the daily exposure of the population to high concentrations. Anthropogenic climate forcing is reduced due to decreased CO_2, CH_4 and tropospheric O_3 precursors. However, this benefit is partially offset by the reduction in PM causing an unintended positive (warming) forcing to climate. It is therefore important to consider both the air quality and climate impact from near-term climate forcers in any future climate and air quality policies.

Acknowledgments

Steven Turnock and Fiona O'Connor would like to acknowledge that support for this work came from the BEIS and DEFRA Met Office Hadley Centre Climate Programme (GA01101) and the UK-China Research and Innovation Partnership Fund through the Met Office Climate Science for Service Partnership (CSSP) China as part of the Newton Fund.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID iDs

S T Turnock https://orcid.org/0000-0002-0036-4627
S Smith https://orcid.org/0000-0003-3248-5607
F M O'Connor https://orcid.org/0000-0003-2893-4828

References

Allen R J, Landuyt W and Rumbold S T 2016 An increase in aerosol burden and radiative effects in a warmer world *Nat. Clim. Change* **6** 269–74

Andrews T, Gregory J M, Webb M J and Taylor K E 2012 Forcing, feedbacks and climate sensitivity in CMIP5 coupled atmosphere-ocean climate models *Geophys. Res. Lett.* **39** 1–7

Colette A *et al* 2015 Is the ozone climate penalty robust in Europe? *Environ. Res. Lett.* **10** 84015

Collins W J *et al* 2011 Development and evaluation of an Earth-System model—HadGEM2 *Geosci. Model Dev.* **4** 1051–75

Doherty R M, Heal M R and O'Connor F M 2017 Climate change impacts on human health over Europe through its effect on air quality *Environ. Heal.* **16** 118

Fiore A M *et al* 2012 Global air quality and climate *Chem. Soc. Rev.* **41** 6663–83

Forster P M, Richardson T, Maycock A C, Smith C J, Samset B H, Myhre G, Andrews T, Pincus R and Schulz M 2016 Recommendations for diagnosing effective radiative forcing from climate models for CMIP6 *J. Geophys. Res. Atmos.* **121** 12460–75

Fortems-Cheiney A, Foret G, Siour G, Vautard R, Szopa S, Dufour G, Colette A, Lacressonniere G and Beekmann M 2017 A 3 °C global RCP8.5 emission trajectory cancels benefits of European emission reductions on air quality *Nat. Commun.* **8** 1–5

Fowler D *et al* 2009 Atmospheric composition change: ecosystems–atmosphere interactions *Atmos. Environ.* **43** 5193–267

Garcia-Menendez F, Monier E and Selin N E 2017 The role of naturalvariability in projections of climatechange impacts on U.S. ozone pollution *Geophys. Res. Lett.* **44** 2911–21

Gidden M J *et al* 2019 Global emissions pathways under different socioeconomic scenarios for use in CMIP6: a dataset of harmonized emissions trajectories through the end of the century, Geosci *Model Dev.* **12** 1443–75

Glotfelty T, He J and Zhang Y 2017 Impact of future climate policy scenarios on air quality and aerosol-cloud interactions using an advanced version of CESM/CAM5: I. Model evaluation for the current decadal simulations *Atmos. Environ.* **152** 222–39

Glotfelty T and Zhang Y 2017 Impact of future climate policy scenarios on air quality and aerosol-cloud interactions using an advanced version of CESM/CAM5: II. Future trend analysis and impacts of projected anthropogenic emissions *Atmos. Environ.* **152** 531–52

Im U *et al* 2018 Influence of anthropogenic emissions and boundary conditions on multi-model simulations of major air pollutants over Europe and North America in the framework of AQMEII3 *Atmos. Chem. Phys.* **18** 8929–52

Isaksen I S A *et al* 2009 Atmospheric composition change: climate–chemistry interactions *Atmos. Environ.* **43** 5138–92

Jacob D J and Winner D A 2009 Effect of climate change on air quality *Atmos. Environ.* **43** 51–63

Jones C D *et al* 2011 The HadGEM2-ES implementation of CMIP5 centennial simulations *Geosci. Model Dev.* **4** 543–70

Kim M J, Park R J, Ho C-H, Woo J-H, Choi K-C, Song C-K and Lee J-B 2015 Future ozone and oxidants change under the RCP scenarios *Atmos. Environ.* **101** 103–15

Kirtman B *et al* 2013 Projections and predictability *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed T F Stocker *et al* (Cambridge and New York, NY: Cambridge University Press)

Lamarque J-F *et al* 2010 Historical (1850–2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols: methodology and application *Atmos. Chem. Phys.* **10** 7017–39

Lee Y, Shindell D T, Faluvegi G and Pinder R W 2016 Potential impact of a US climate policy and air quality regulations on future air quality and climate change *Atmos. Chem. Phys.* **2009** 5323–42

Lelieveld J, Evans J S, Fnais M, Giannadaki D and Pozzer A 2015 The contribution of outdoor air pollution sources to premature mortality on a global scale *Nature* **525** 367–71

Li M, Zhang D, Li C-T, Mulvaney K M, Selin N E and Karplus V J 2018 Air quality co-benefits of carbon pricing in China *Nat. Clim. Change* **8** 1

Mulcahy J P *et al* 2018 Improved aerosol processes and effective radiative forcing in HadGEM3 and UKESM1 *J. Adv. Model. Earth Syst.* **10** 2786–805

Myhre G *et al* 2013 Anthropogenic and natural radiative forcing *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernemental Panel on Cliamte Change* ed T F Stocker *et al* (Cambridge and New York, NY: Cambridge University Press)

Rao S *et al* 2016 A multi-model assessment of the co-benefits of climate mitigation for global air quality *Environ. Res. Lett.* **11** 124013

Rao S *et al* 2017 Future air pollution in the shared socio-economic pathways *Glob. Environ. Change* **42** 346–58

Rasmussen D J, Hu J, Mahmud A and Kleeman J M 2013 The ozone climate penalty: past, present and future *Environ. Sci. Technol.* **47** 14258–66

Reddington C L *et al* 2017 The global aerosol synthesis and science project (GASSP): measurements and modeling to reduce uncertainty *Bull. Am. Meteorol. Soc.* **98** 1857–77

Reis L A, Drouet L, van Dingenen R and Emmerling J 2018 Future global air quality indices under different socioeconomic and climate assumptions *Sustainability* **10** 1–27

Schucht S *et al* 2015 Moving towards ambitious climate policies: monetised health benefits from improved air quality could offset mitigation costs in Europe *Environ. Sci. Policy* **50** 252–69

Schultz M G *et al* 2017 Tropospheric Ozone assessment report: database and metrics data of global surface Ozone observations *Elem. Sci. Anth.* **5** 58

Shen L, Mickley L J and Murray L T 2017 Influence of 2000–2050 climate change on particulate matter in the United States: results from a new statistical model *Atmos. Chem. Phys.* **17** 4355–67

Shindell D T *et al* 2012 Simultaneously mitigating near-term climate change and improving human health and food security *Science* **335** 183–9

Silva R A *et al* 2017 Future global mortality from changes in air pollution attributable to climate change *Nat. Clim. Change* **7** 647–51

Solazzo E *et al* 2017 Evaluation and error apportionment of an ensemble of atmospheric chemistry transport modeling systems: multivariable temporal and spatial breakdown *Atmos. Chem. Phys.* **17** 3001–54

Stohl A *et al* 2015 Evaluating the climate and air quality impacts of short-lived pollutants *Atmos. Chem. Phys.* **15** 10529–66

Thomson A M *et al* 2011 RCP4.5: a pathway for stabilization of radiative forcing by 2100 *Clim. Change* **109** 77–94

Turnock S T *et al* 2015 Modelled and observed changes in aerosols and surface solar radiation over Europe between 1960 and 2009 *Atmos. Chem. Phys.* **15** 9477–500

Turnock S T *et al* 2016 The impact of European legislative and technology measures to reduce air pollutants on air quality, human health and climate *Environ. Res. Lett.* **11** 24010

US EPA 2011 *The Benefits and Costs of the Clean Air Act from 1990 to 2020: Summary Report* U.S. Environmental Protection Agency Office of Air and Radiation

Vandyck T, Keramidas K, Kitous A, Spadaro J V, Van Dingenen R, Holland M and Saveyn B 2018 Air quality co-benefits for

human health and agriculture counterbalance costs to meet Paris Agreement pledges *Nat. Commun.* **9** 1–11

von Schneidemesser E *et al* 2015 Chemistry and the linkages between air quality and climate change *Chem. Rev.* **115** 3856–97

West J J, Smith S J, Silva R A, Naik V, Zhang Y, Adelman Z, Fry M M, Anenberg S and Horowitz L W 2013 Co-benefits of mitigating global greenhouse gas emissions for future air quality and human health *Nat. Clim. Change* **3** 885–9

Young P J *et al* 2013 Pre-industrial to end 21st century projections of tropospheric ozone from the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP) *Atmos. Chem. Phys.* **13** 2063–90

Young P J *et al* 2018 Tropospheric Ozone Assessment Report: assessment of global-scale model performance for global and regional ozone distributions, variability, and trends *Elem. Sci. Anth.* **6** 10

Zhang Y, Bowden J H, Adelman Z, Naik V, Horowitz L W, Smith S J and West J J 2016 Co-benefits of global and regional greenhouse gas mitigation for US air quality in 2050 *Atmos. Chem. Phys.* **16** 9533–48

Zhang Y, Smith S J, Bowden J H, Adelman Z and West J J 2017 Co-benefits of global , domestic , and sectoral greenhouse gas mitigation for US air quality and human health in 2050 *Environ. Res. Lett.* **12** 114033