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Global health and economic impacts of future ozone pollution

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Abstract

We assess the human health and economic impacts of projected 2000–2050 changes in ozone pollution using the MIT Emissions Prediction and Policy Analysis - Health Effects (EPPA-HE) model, in combination with results from the GEOS-Chem global tropospheric chemistry model of climate and chemistry effects of projected future emissions. We use EPPA-HE to assess the human health damages (including mortality and morbidity) caused by ozone pollution, and quantify their economic impacts in sixteen world regions. We compare the costs of ozone pollution under scenarios with 2000 and 2050 ozone precursor and greenhouse gas emissions (using the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) A1B scenario). We estimate that health costs due to global ozone pollution above pre-industrial levels by 2050 will be \$580 billion (year 2000\$) and that mortalities from acute exposure will exceed 2 million. We find that previous methodologies underestimate costs of air pollution by more than a third because they do not take into account the long-term, compounding effects of health costs. The economic effects of emissions changes far exceed the influence of climate alone.

Keywords: ozone, air pollution, climate, health

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1. Introduction

Tropospheric ozone is an air pollutant that causes adverse human health impacts. Increasing industrialization without emissions controls will increase releases of chemical precursors to ozone, such as nitrogen oxides (NO_x) and volatile organic compounds (VOCs). Changes in climate, including increasing temperature and other changing meteorological variables, have a complex effect on ozone concentrations (Mickley 2007). Previous studies have explored the impacts of future emissions and climate on surface ozone concentrations using climate and chemical transport models. We apply these results to an economic model to assess the potential future health and economic damages of ozone due to changing emissions and climate in 2050.

Previous research has projected the influence of both climatic change and future emissions under a variety of scenarios on surface ozone levels in the United States and elsewhere (Wu *et al* 2008a, 2008b, Hogrefe *et al* 2004, Racherla and Adams 2006, Murazaki and Hess 2006, Royal

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Society 2008, Racherla and Adams 2009). While there is substantial variability among models of the climate impact of ozone, most models predict a decrease in surface ozone background due to the effect of water vapour, and surface ozone increases of 1–10 ppb driven primarily by temperature in polluted mid-latitude regions (Jacob and Winner 2009). For example, Racherla and Adams (2006) used a global climate model to project a 5% decrease in the global tropospheric ozone burden under the Intergovernmental Panel on Climate Change (IPCC) SRES A2 scenario, but an increase of 1–5 ppb in some polluted regions including the eastern United States. The Royal Society (2008) assessed projected trends in tropospheric ozone due to emissions and climate changes and implications for human health and vegetation. They found that mean O_3 concentrations will likely increase over polluted land regions due to climatic changes, but would decline where strong precursor emissions controls are put into place.

Related studies have quantified the impacts of present and future ozone pollution on human health (Bell *et al* 2007, West *et al* 2007, Knowlton *et al* 2004). West *et al* (2007) examined the effects of future changes in global ozone under three different emissions scenarios on premature mortalities, and calculated up to 460 000 reduced mortalities with a Maximum Feasible Reduction (MFR) scenario compared to the SRES A2 scenario. Bell *et al* (2007) calculated an average of 0.31% increase in cardiovascular disease mortality under the SRES A2 scenario for the 2050s. In general, studies have projected increases in morbidity and mortality from tropospheric ozone (Ebi and McGregor 2008).

Previous efforts to estimate the potential future economic impacts of ozone-related health damages have multiplied ambient concentrations by concentration–response factors to determine number of cases or deaths, and then imposed a cost per case calculated by a variety of methods including willingness-to-pay (WTP) data (Bell *et al* 2008). West *et al* (2007), for example, calculated the global economic benefit of a ∼1 ppb ozone decrease by multiplying the number of avoided mortalities by a value of a statistical life (VSL). A few recent studies have used a more detailed economic modelling approach to assess the feedbacks of pollution damages onto the economy (Holland *et al* 1999, Mayeres and Van Regemorter 2008).

Here, we apply a computable general equilibrium (CGE) economic modelling approach to assess damages from future health impacts of ozone, using results from an atmospheric chemical transport/general circulation model analysis of the effects of 2000–2050 emissions and climate change on global surface ozone. The CGE modelling approach takes into account that economic damages accumulate over time due to resource diversions for health care, including both morbidity and mortality due to ozone exposure, and accounts for the increasing value of lost work and leisure time as incomes and productivity rise. We use these results to calculate global direct and indirect costs of present and potential future health damages from ozone pollution.

2. Methods

2.1. Overall analysis

Using atmospheric model output, we first calculate population-weighted ozone for sixteen world regions under four different precursor emissions and climate cases. We use these population-weighted concentrations as input to a CGE model to calculate human health impacts and economic costs related to these ozone concentrations. We then use Monte Carlo analysis to assess the uncertainty in our epidemiological and cost assumptions.

2.2. Atmospheric model description

2.2.1. General description. We use results for 2000 and 2050 ozone concentrations from the GEOS-Chem Chemical Transport Model (CTM) (Wu *et al* 2008a, 2008b). GEOS-Chem has been widely used by research groups around the world for a broad range of applications in atmospheric chemistry and air quality. A general description of the model can be found at http://acmg.seas.harvard.edu/geos/index.html. As used here, the model has a horizontal resolution of 4° latitude × 5° longitude and a chemistry and transport time step of 30 min. GEOS-Chem has been extensively evaluated and documented in over 100 refereed journal publications (e.g., Fiore *et al* 2002a, 2002b, 2003, Li *et al* 2002, 2004, Hudman *et al* 2007). These provide considerable diagnostic information on model comparisons with observations. GEOS-Chem was successfully applied in earlier studies of the potential effects of global change on air quality in the United States (Fiore *et al* 2002b, Wu *et al* 2008a, 2008b, Pye *et al* 2009). While the resolution of the model does not resolve local ozone maxima, it does not induce significant mean bias and can still capture the major influences on ozone variability (Fiore *et al* 2003, Wu *et al* 2008a).

2.2.2. Input data. In the GEOS-Chem future climate simulation used here (Wu *et al* 2008a, 2008b), both climate and ozone precursor emissions are based on the IPCC A1B scenario (IPCC 2001). Climate changes are simulated by the NASA/GISS GCM 3 (Rind *et al* 2007) and are used to drive GEOS-Chem as described by Wu *et al* (2007). In the A1B scenario, emissions of fossil fuel NO_x decrease in developed countries (−40% in the United States) but increase by 90% globally. Detailed emissions for other ozone precursors from both anthropogenic and natural sources are given in Wu *et al* (2008a).

2.2.3. Model simulation. Annual mean afternoon (1300–1700 h local time) ozone, a metric comparable to daily maximum 8 h average ozone, is archived for three-year climatic periods. Four cases are used, following Wu *et al* (2008b): (1) year 2000 ozone precursor emissions and climate; (2) 2000 precursor emissions and 2050 climate; (3) 2050 precursor emissions and 2000 climate; and (4) 2050 precursor emissions and 2050 climate. This scenario design allows diagnosis of ozone changes due to only precursor emission changes, only climate change, and combined changes

Table 1. Concentration–response functions and costs for Europe region. Sources: Bickel and Friedrich (2005), Holland *et al* (1999, 2005), Matus (2005).

Outcome	Concentration–response function[a]	95% confidence interval[b]	Cost EU[c] (\$2000)	Std error cost[d]	Cost China (\$2000)
Mortality from acute exposure	0.03%[e]	(0.01%, 0.04%)	23 000	3100	690
Respiratory hospital admission (adults >65 years)	1.25×10^{-5}	$(-5.0 \times 10^{-6}, 3.0 \times 10^{-5})$	1800	570	290
Respiratory symptom day	3.3×10^{-2}	$(5.7 \times 10^{-3}, 6.3 \times 10^{-2})$	35	11	<1
Minor restricted activity day	1.15×10^{-2}	$(4.4 \times 10^{-3}, 1.9 \times 10^{-2})$	35	11	<1
Asthma attack	4.29×10^{-3}	$(3.3 \times 10^{-4}, 8.3 \times 10^{-3})$	49	16	4.6
Bronchodilator usage	7.30×10^{-2}	$(-2.6 \times 10^{-2}, 1.6 \times 10^{-1})$	0.92	0.29	<1
Lower respiratory symptoms (wheeze) in children	1.60×10^{-2}	$(-4.3 \times 10^{-2}, 8.1 \times 10^{-2})$	35	11	<1

[a] Units are cases yr^{-1} person^{-1} $\mu\mathrm{g}^{-1}$ m^3.

[b] Normal distributions applied for symmetric confidence intervals, and beta distributions applied for asymmetric confidence intervals. Confidence intervals are cut off at zero and negative values are not assessed.

[c] Converted from €2000 using exchange rate \$1 = €1.085 (mean for year 2000).

[d] Normal distributions applied for costs.

[e] Units are Δ annual mortality rate $\mu\mathrm{g}^{-1}$ m^3

as the difference between these simulations. For input to the human health and economic model described below, we calculate population-weighted annual average afternoon ozone concentrations for each region, for scenarios with and without climate and emissions changes. We use the gridded population distribution for 2000 from the Center for International Earth Science Information Network (CIESIN 2005), and apply region-specific growth rates to 2050 for each economic model region (described below) (United Nations 2007). We assume that the distribution of population within each region will remain constant as total regional population increases in the period 2000–2050 so that we use the same within-region weighting factors for 2000 and 2050.

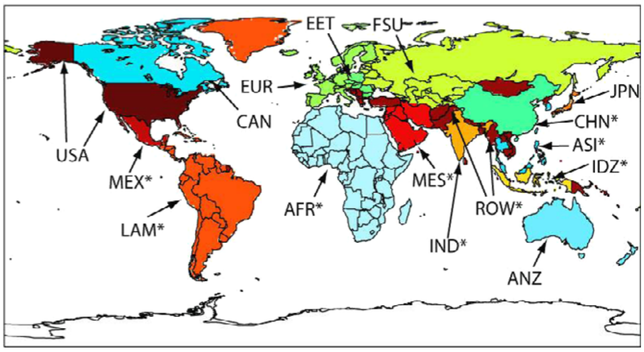


Figure 1. EPPA-HE Regions. Asterisks represent regions referred to in text as developing.

2.3. *Human health and economic model description*

2.3.1. General description. We use the MIT Emissions Prediction and Policy Analysis model (Paltsev *et al* 2005) with extensions to value health impacts of ozone (EPPA-Health Effects or EPPA-HE) (Matus *et al* 2008). EPPA is a CGE model of the world economy. EPPA-HE has previously been applied to assess the benefits of the US Clean Air Act (Matus *et al* 2008), the costs of historical air pollution in China (Matus 2005), and the costs of air pollution and potential benefits of regulation in the European Union (Nam *et al* 2009).

Briefly, the model calculates health impacts and related costs to the economy (lost labour, services, and leisure time) for a given mean concentration of pollutant in each of sixteen world regions. The regional structure of the model is shown in figure 1. The model takes as input the population-weighted concentration in each region, and calculates cases and associated costs using a five-year time step. Resources devoted to health care become unavailable to the rest of the economy, and labour and leisure time lost as a result of illness or death is valued at prevailing wage rates. A full description of the economic assumptions of the EPPA-HE model is presented by Matus *et al* (2008).

2.3.2. Input data for health assessment. Table 1 shows the concentration–response functions we use to link ozone concentrations to health outcomes in EPPA-HE, and their related economic costs in the Europe (EUR in figure 1) and China (CHN) regions. Following Bickel and Friedrich (2005), we specify these functions and related costs in (year 2000) \$ for the Europe region. The values of health endpoints here reflect both the cost of treating illness (such as hospital visits) as well as survey information on willingness-to-pay (WTP) to avoid damages. For mortality from acute exposure, we assume that each reflects 0.5 years of life lost, and apply a value of a statistical life year (VOLY) approach as recommended by Bickel and Friedrich (2005). We adjust costs for other developed regions using purchasing power parity (PPP) (Heston *et al* 2002). For developing regions (those marked with an asterisk in figure 1), we use cost estimates developed for China (Matus 2005) and adjust costs for other developing country regions based on PPP relative to China.

All endpoints are considered linear without a threshold, consistent with data from Bell *et al* (2006) that even low levels of ozone are associated with increased risk of mortality.

For mortality from acute exposure, the exposure response function is given as an elevation of the baseline mortality rate. We use baseline mortality rates from the World Bank Global Burden of Disease study (Lopez *et al* 2006), for high income (for developed regions) and low–middle income countries (for developing regions). Age distributions of populations, used in calculating effects for children and adults over age 65, are applied separately for developing and developed regions (United Nations 2007).

2.3.3. Model simulation and uncertainty analysis. We calculate economic impacts from ozone using the EPPA reference scenario, which is consistent with an economy that produces global greenhouse gas emissions within 15% of A1B emissions to 2050. We assess the economic impacts of ozone pollution by calculating the change in economic welfare (defined as macroeconomic consumption plus the value of leisure time) between simulations with varying levels of ozone.

We assess the uncertainties in calculated mortalities and costs resulting from both the uncertainties in concentration–response functions and economic valuation of health endpoints, using a probabilistic approach with Monte Carlo sampling. We conduct our uncertainty analysis similarly to the methodology used by Webster *et al* (2008). We construct probability distributions of concentration–response functions and associated costs, based on probabilistic ranges from Bickel and Friedrich (2005) and Holland *et al* (2005) (table 1). We assume that concentration–response functions are correlated (details in supporting information table S.1, available at stacks.iop.org/ERL/4/044014/mmedia) and that costs are correlated at $r = 0.9$. Using Latin Hypercube sampling, we select 400 sets of inputs for each case, with concentration–response functions and associated costs varying, and simulate resulting welfare change for each case using EPPA-HE.

3. Results

3.1. Population-weighted ozone concentrations

Table 2 presents population-weighted average regional ozone concentrations for each EPPA region for both the year 2000 and projected 2050 concentrations with changed precursor emissions and climate. Also shown are changes in ozone due to climate alone, diagnosed from a model simulation with 2050 climate and 2000 precursor emissions, and due to emissions alone, from a simulation with 2050 precursor emissions and 2000 climate. The net 2000–2050 ozone change is equal to the sum of these two contributions, indicating they are independent of each other in these simulations.

Figure 2 shows population-weighted ozone concentration for Asia. Panel (a) shows O_3 concentrations in Asia in 2050 climate, with constant (year 2000) ozone precursor emissions, while panel (b) shows the changes in O_3 due to climate change from present-day conditions (year 2000 climate and precursor emissions). Panels (c) and (d) show the total population in areas where O_3 decreases and increases, respectively, due to climatic changes.

Table 2. Population-weighted ozone concentrations by EPPA region, and change in ozone due to climate, emissions, and net change 2000–2050, from GEOS-Chem.

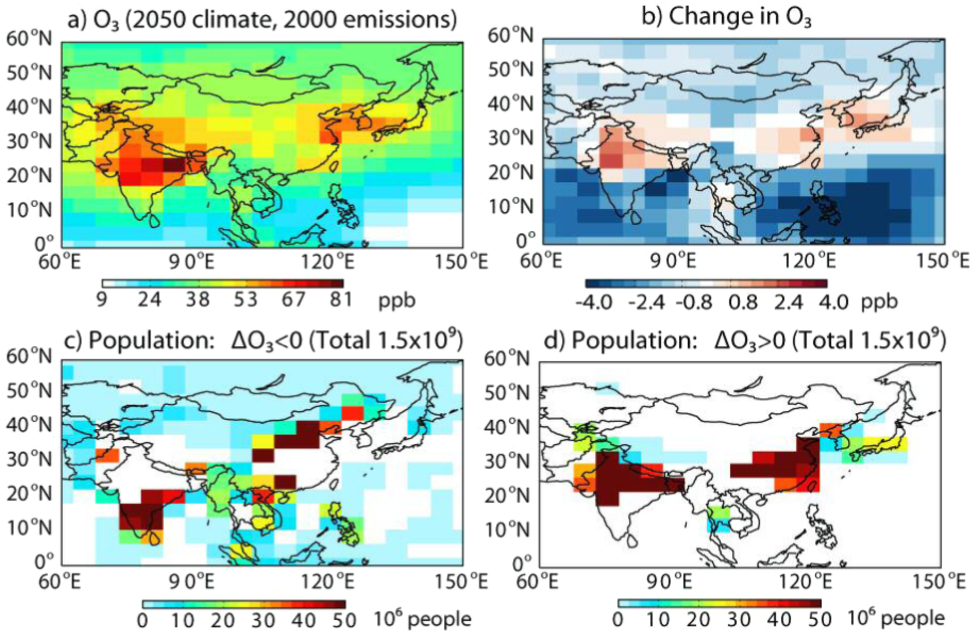
Region	2000 $[O_3]$	2050 $[O_3]$	ΔO_3, climate	ΔO_3, emissions	ΔO_3 (2050–2000)
AFR	33.2	43.2	−0.2	10.3	10.1
ANZ	31.3	30.4	0.0	−0.9	−0.9
ASI	41.4	53.4	0.1	11.9	12.0
CAN	41.7	37.3	0.2	−4.6	−4.4
CHN	47.7	55.7	−0.1	8.2	8.1
EET	43.2	43.5	−1.1	1.3	0.2
EUR	43.5	45.2	0.2	1.5	1.7
FSU	40.4	39.3	−0.9	−0.2	−1.1
IDZ	29.5	44.0	−1.2	15.7	14.4
IND	61.0	85.4	0.4	24.0	24.4
JPN	50.9	48.4	0.9	−3.4	−2.5
LAM	28.3	39.5	0.3	10.9	11.2
MES	48.4	58.8	−0.5	10.9	10.4
MEX	46.3	53.4	−1.6	8.6	7.1
ROW	48.4	60.1	−0.2	12.0	11.8
USA	50.1	45.2	0.2	−5.1	−4.9

3.2. Health outcomes

Figure 3 shows the change in mortalities from acute exposure due to ozone concentration changes, separating the influence of changing climate alone (panel (a)), emissions changes alone (panel (b)), and climate and emissions changes together (panel (c)). We also calculate the number of mortalities in 2050 that result from ozone exposure above pre-industrial levels (a mean population-weighted exposure of 10 ppb for each region) (panel (d)). The total number of mortalities in each of 16 regions is calculated by EPPA-HE. For figure 3, we spatially distribute mortalities within each region according to the projected change in O_3 concentrations between present day and in 2050 (panels (a)–(c)), and change in 2050 relative to the pre-industrial (10 ppb) level (panel (c)). EPPA-HE projects an increase of 817 000 mortalities under 2050 A1B ozone precursor emissions (with constant climate). All regions except the US (in which emissions decrease substantially in the A1B scenario) show net increases in mortalities. Thus, the net effect of climate and precursor emissions (figure 3, panel (b)) is to increase mortalities by 812 000 globally, with increases virtually everywhere except for the eastern US. Detailed results by EPPA region are presented in table S.2 (available at stacks.iop.org/ERL/4/044014/mmedia). Our Monte Carlo analysis indicates a 95% probability interval of 350 000–2300 000 mortalities for this scenario, taking into account uncertainty in concentration–response functions. The difference in mortalities between projected 2050 levels (including climate and precursor emissions changes) and a pre-industrial exposure level of 10 ppb is estimated to exceed 2 million mortalities, with a 95% probability interval of 560 000–3600 000 (figure 3, panel (d)).

3.3. Economic costs of health impacts

Figure 4 shows the economic (welfare) losses (including leisure losses) due to ozone-related health impacts from

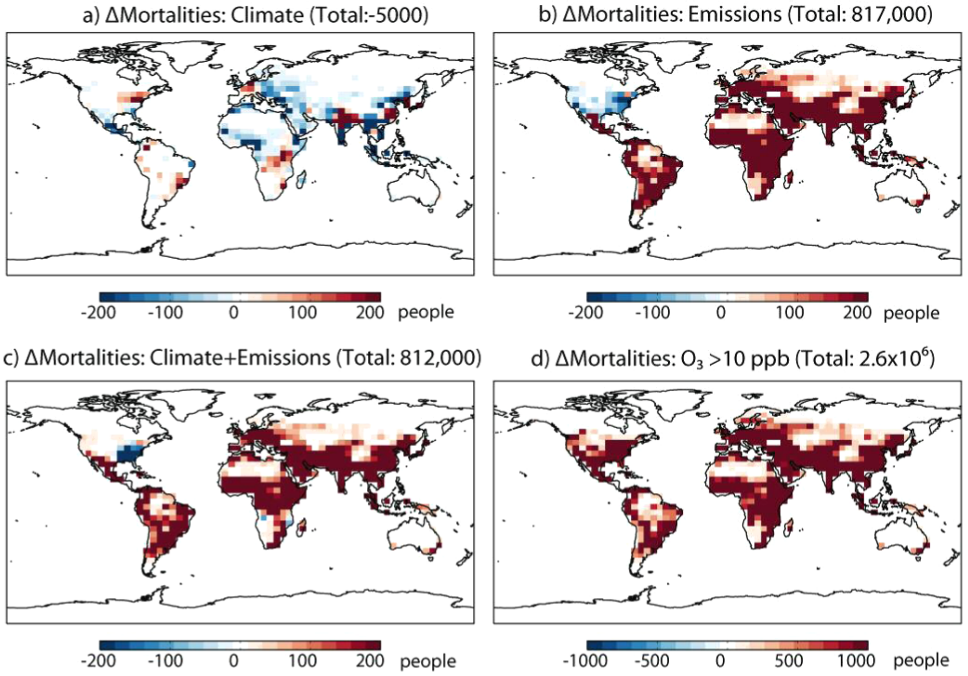

a) O_3 (2050 climate, 2000 emissions)

b) Change in O_3

c) Population: $\Delta O_3<0$ (Total 1.5×10^9)

d) Population: $\Delta O_3>0$ (Total 1.5×10^9)

Figure 2. Model simulated O_3 change in Asia relative to population. Panel (a) shows O_3 concentrations for 2050 climate and 2000 emissions. Panel (b) shows the overall projected change in ozone due to climate. Panel (c) shows total population in areas where ozone decreases due to climate, and panel (d) shows total population in areas where ozone increases due to climate.


a) ΔMortalities: Climate (Total:-5000)

b) ΔMortalities: Emissions (Total: 817,000)

c) ΔMortalities: Climate+Emissions (Total: 812,000)

d) ΔMortalities: O_3 >10 ppb (Total: 2.6×10^6)

Figure 3. Change in mortalities from acute O_3 exposure due to (a) climatic change (with 2000 precursor emissions); (b) precursor emission changes (under 2050 climate); (c) climate and precursor emission changes in 2050; and (d) ozone enhancements in 2050 above pre-industrial exposures (10 ppb). Mortality data is calculated for 16 world regions by EPPA-HE using population-weighted ozone concentrations (see table 2). Mortalities are distributed regionally based on ozone changes in each scenario. Note difference in scale for panel (d). Colour scales are saturated at highest and lowest values.

climate change alone (panel (a)), precursor emissions changes alone (panel (b)), climate and precursor emissions together (panel (c)), and excess ozone greater than 10 ppb (panel (d)). Welfare losses are calculated for each region from EPPA-HE; for presentation in figure 4, data are distributed within each region based on population. We calculate an annual welfare loss of \$120 billion in 2050 due to emissions changes, and thus a net cost of \$120.8 billion due to climate and emissions changes. In figure 4(c), we show the total cost of ozone pollution above pre-industrial background, which is \$580 billion in 2050. As shown in the figure, welfare losses occur in all regions.

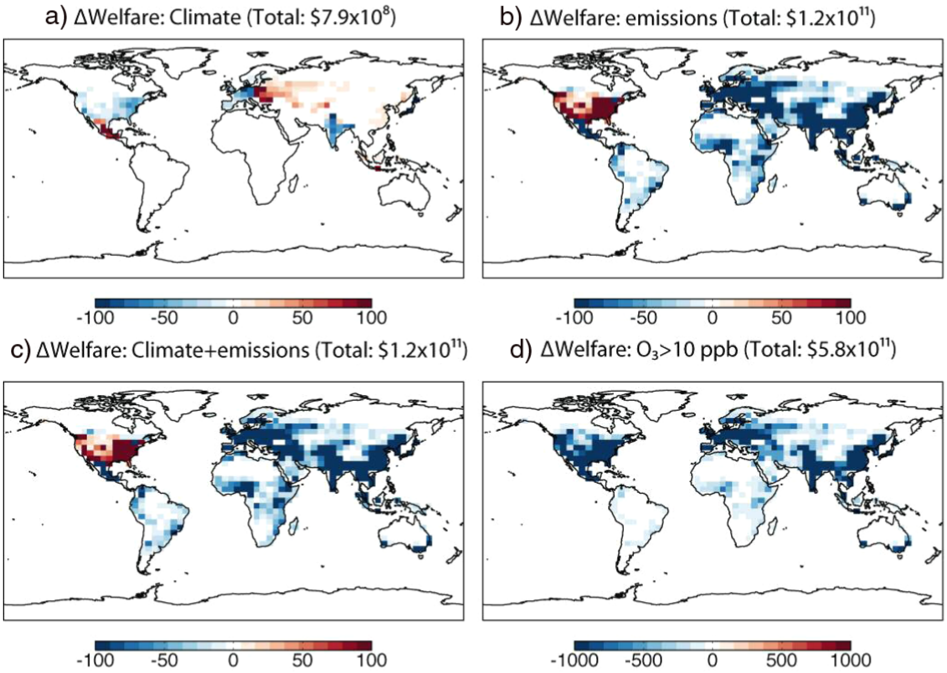


Figure 4. Change in economic welfare (consumption + leisure) from ozone-related health impacts due to (a) climatic change (with 2000 precursor emissions); (b) emission changes (2050 climate); (c) climate and precursor emission changes in 2050; and (d) ozone enhancements in 2050 above pre-industrial exposures (10 ppb). Welfare change is calculated for 16 world regions by EPPA-HE using population-weighted ozone concentrations (see table 2). Welfare is regionally distributed based on population. All values are in year 2000$. Note difference in scale for panel (d). Colour scales are saturated at highest and lowest values.

As shown in figure 4(a), climate change results in an annual global net loss of welfare of $790 million by 2050 (in year 2000$), undiscounted. While some regions show net welfare gains (due to decreased ozone), these gains are outweighed by loss of welfare due to ozone increases in high income regions (United States, Europe and Japan). Detailed results for each region are presented in table S.3 (available at stacks.iop.org/ERL/4/044014/mmedia).

Monte Carlo analysis shows the influence of both concentration–response and economic uncertainty on our welfare results. Figure 5 shows the difference in welfare between the scenario with climate and emission changes to 2050 and 2000 ozone levels (first row), and between 2050 and the pre-industrial background (second row). We calculate a 95% probability interval of $13 billion–$190 billion for the annual welfare loss due to climate and emissions changes from 2000–2050. For the total cost of ozone pollution above pre-industrial background, the 95% probability interval is $101 billion–$1.53 trillion. These uncertainties only take into account the uncertainties in the concentration–response factors and the economic valuation of impacts, and do not take into account additional uncertainties in future emissions and climate.

4. Discussion

4.1. Projected changes in population-weighted ozone

Population-weighted concentrations generally change more due to 2000–2050 precursor emissions changes than climate change. In most developing regions, precursor emissions increases result in population-weighted ozone increases. Climate change can have a positive or negative effect on population-weighted ozone in different regions.

As shown in figure 2 for Asia, the total population is roughly equal (1.5×10^9 people) in areas where ozone is increasing and decreasing. Areas of high population where ozone is projected to increase due to climate include northern India and eastern China, where ozone levels (panel (a)) are particularly high. The population-weighted totals thus indicate a 0.1 ppb decrease due to climate change in China, and a 0.4 ppb climate-driven increase in India. This suggests a strong subregional variation in the effects of climate on ozone in urban areas, which could be further explored with regional atmospheric and economic modelling.

In contrast to previous findings of an increased trend of ozone with climate change in urban, high-ozone areas (Jacob and Winner 2009), we find that average population-weighted ozone changes due to climate are very small. Consistent with previous studies, ozone increases on the order of a few ppb are present in many urban regions in the model simulation of Wu *et al* (2008a), but in most cases they are offset by decreases in other highly populated regions, leading to a net change near zero.

Population-weighted annual average 8 h maximum ozone concentrations calculated from Wu *et al* (2008a) by region (ranging from 29.5 to 61.0 ppb, see table 2) vary more than those calculated by West *et al* (2007) using the LMDz-INCA chemistry-climate model for the year 2000, which range from a low of 39.3 ppb in Asia to a high of 46.4 in North America. In developing regions, surface ozone concentration measurements are not available; thus, model predictions are difficult to

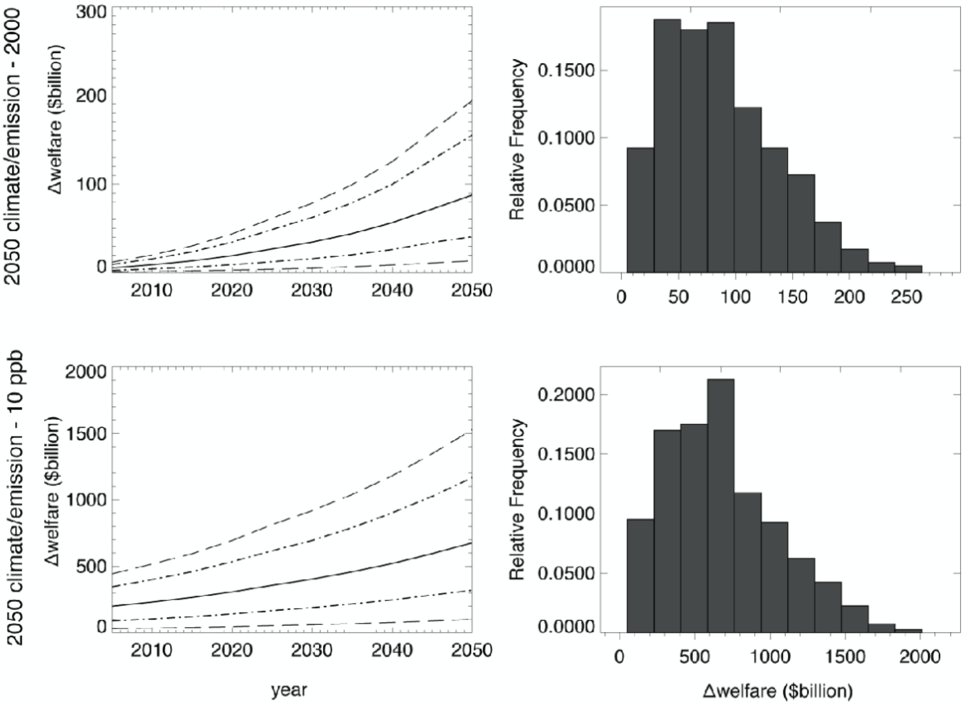


Figure 5. Uncertainty in total global loss in economic welfare (consumption+leisure) from ozone-related health impacts due to (first row) climate and emission changes in 2050 relative to 2000, and (second row) ozone enhancements in 2050 above pre-industrial exposure (10 ppb), based on a 400 sample Monte Carlo simulation. Left column shows median (solid), 67% (dash–dot) and 95% (dashed) probability intervals. Right column shows frequency distribution of welfare loss for year 2050. All values are in year 2000$. Note that the median welfare change for the ensemble is not equivalent to the welfare change calculated with mean inputs.

validate. We use the estimates of West *et al* (2007) (table S.4, available at stacks.iop.org/ERL/4/044014/mmedia) as a sensitivity test to assess the influence of atmospheric model and emissions scenario uncertainty on our results, discussed further below.

4.2. Projected mortality impacts

Overall, EPPA-HE predicts 5000 fewer mortalities due to acute O_3 exposure in 2050 relative to 2000 when taking into account climate change alone (constant 2000 precursor emissions). However, as shown in figure 3, climate change leads to mortality increases in some regions and decreases in others. Specifically, the eastern US, parts of Europe, east Africa, north India, and eastern China are areas where mortalities will increase; this pattern follows the pattern of ozone changes due to climate. Overall, EPPA-HE predicts a net increase in mortalities in seven regions (USA, ASI, CAN, EUR, IND, JPN, and LAM, see table S.2 (available at stacks.iop.org/ERL/4/044014/mmedia) and figure 1 for region information) and net decreases in others. As expected from the ozone changes (figure 2), the increased mortality from emissions changes far outweighs the climate impact.

West *et al* (2007) previously assessed potential changes in global mortalities from acute exposure using four different scenarios. Under their MFR scenario, they calculate that emissions reductions could reduce global mortalities by about 460 000 relative to ozone predicted by their application of the SRES A2 scenario in 2030. To compare our results to their approach, we ran EPPA-HE to 2030 with the population-weighted concentrations reported in their study. For the same scenario, we project a larger number of avoided mortalities (780 000), about 70% higher but within their uncertainty range using different concentration–response functions. We also project a decrease of 130 000 mortalities under maximum feasible reduction relative to current legislation (lower concentrations than A2), which is less than the 267 000 predicted by West *et al* (2007), but again within their uncertainty bounds. In contrast to West *et al* (2007), who assumed a log–linear response function and a threshold of 25 ppb for health effects, we assume a linear response without threshold and a higher concentration–response function, as described above. Log–linear curves have a steeper response at lower concentrations, and less response at higher concentrations, consistent with the comparison here.

4.3. Projected economic impacts

Similar to the results for mortalities alone, the change in welfare due to emissions changes in the A1B scenario far exceeds the difference due to climate change alone. Using EPPA-HE, we can calculate the compounding effect of ozone pollution between 2000 and 2049 on the 2050 economy. Economic effects in earlier years reduce the overall level of the economy and savings and investment in those years that then lead to a lower stock of capital in succeeding years. We calculate this effect in EPPA-HE by the difference between our simulation in 2050, and a simulation with pre-industrial ozone in 2050 (10 ppb). From this scenario, we calculate that ∼40% of economic losses ($240 billion) result from the accumulated economic burden of previous ozone concentrations (2000–2049). This is not taken into account in most economic calculations of environmental health impacts.

For comparison, we also calculate the potential welfare gains under the West *et al* (2007) MFR scenario relative to SRES A2 for 2030, and with concentration trends linearly extrapolated to 2050. We estimate that changes projected under this scenario would lead to a global welfare increase of $66 billion by 2030, and $170 billion by 2050. This suggests that emissions changes to 2050 have the potential to affect ozone-related health damages ranging from $120 to 170 billion.

4.4. Uncertainties

It is important to recognize that there are many uncertainties in any effort to quantify the human health and economic impacts of ozone concentrations. While we have quantified the influence of concentration–response functions and in the economic valuation of predicted health endpoints, there are model uncertainties in both economic and atmospheric simulations that are difficult to quantify. With respect to the atmospheric simulations, there are differences in various atmospheric model projections of future ozone concentrations (Royal Society 2008). The trajectory of future emissions is unknown, and we assess only one particular scenario here. In particular, the A1B scenario does not take into account potential actions to limit emissions outside developed regions such as recent legislation to implement emissions limits. With respect to the health and economic simulations, the CGE model parameterizations of the economy are characterized by some uncertainty in parameters such as GDP growth and elasticities of substitution. It is unknown whether concentration–response functions developed from studies in Europe and the US are applicable outside these regions, due to different population health baselines, population age structures, and other differences. If ozone concentration effects exhibit a threshold, our analysis could overestimate ozone impacts. In contrast, analyses that multiply a value of statistical life (VSL) by number of avoided mortalities would imply a much higher number. Future applications of the methodology presented here could be used to assess additional future emissions scenarios and conduct further uncertainty analyses.

5. Conclusions and policy implications

We assessed the human health and related economic impacts of present and future (2050) air pollution due to ozone, using the EPPA-HE model applied to results a GEOS-Chem global 3D tropospheric chemistry simulation for the IPCC A1B scenario. We found that ozone changes due to climate and precursor emission changes lead in 2050 to 817 000 additional mortalities (95% probability interval of 350 000–2300 000), and welfare losses of $120 billion (95% range of 13 billion–190 billion); and that climate change contributes only $790 million to the median loss. We further calculated that ozone pollution above pre-industrial background leads to >2 million (95% range of 560 000–3600 000) mortalities in 2050, and welfare costs of $580 billion (95% range of $101 billion–$1.53 trillion). For comparison, our 2050 GDP projection in the US for the case with 2050 climate and precursor emissions is $41 trillion ($2000), and for the world is $149 trillion. Thus, $580 billion is 0.4% of world GDP and 1.3% of US GDP. We estimate that 40% of the median 2050 cost reflects the accumulated economic burden of previous elevated ozone.

Though ozone concentration changes due to climate change vary in sign and magnitude in different regions, we nevertheless calculate a net global welfare loss due to climate-related ozone changes under the A1B scenario. The magnitude of changes due to emissions trajectories, however, far exceeds the climate signal, suggesting that future analyses could consider the effects of different emissions projections. Our analysis suggests that potential reductions in ozone emissions precursors such as NO_x and VOCs could have substantial economic benefits due to human health improvements.

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