

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 that simulated climate and chemistry effects of IPCC SRES emissions. We use EPPA to assess the human health damages (including acute mortality and morbidity outcomes) 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 (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 acute mortalities 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.

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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,b, Hogrefe *et al* 2004, Racherla and Adams 2006, Murazaki and Hess 2006, 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.

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 concentrations by exposure-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 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. 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* 1998, Mayeres and Van Regemorter 2008).

Here, we go beyond previous analyses by applying 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 goes beyond previous studies by taking 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 accounting 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. Model Description

2.1. Atmospheric model

We use results for 2000 and 2050 ozone concentrations from Wu *et al* (2008a, 2008b), for which 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 the GEOS-Chem Chemical Transport Model (CTM) 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). Annual mean afternoon (1300-1700h local time) ozone, a metric comparable to daily maximum 8-hour average ozone, is archived for three-year climatic periods. Four cases are used: (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 as the difference between these simulations.

2.2. Human health and economic model

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 U.S.

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 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). The EPPA reference scenario, used here for economic analysis, is consistent with an economy that produces global greenhouse gas emissions within 15% of A1B emissions to 2050.

Table 1 shows the exposure-response functions used to link ozone concentrations to health outcomes in EPPA-HE, and related economic costs in Europe and in China. Following Bickel and Friedrich (2005), we specify these functions and related costs in (year 2000) \$ for the European region. For other developed regions, costs are adjusted using purchasing power parity (PPP) (Heston *et al* 2002) For developing regions, 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). Population distributions are applied separately for developing and developed regions (United Nations 2007). 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).

We assess the uncertainties in calculated mortalities and costs resulting from both the uncertainties in exposure-response functions and economic valuation, 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 exposure-response functions and associated costs, based on probabilistic ranges from Bickel and Friedrich (2005) and Holland *et al* (2005) (Table 1). We assume that exposure-response functions are correlated (details in Supporting Information Table S.1) and that costs are correlated at $r=0.9$. Using Latin Hypercube sampling, we select 400 sets of inputs for each case, with exposure-response functions and associated costs varying, and simulate resulting welfare change for each case using EPPA-HE.

3. Population-weighted ozone concentrations

For input to EPPA, we calculate population-weighted annual average afternoon ozone concentrations for each region, for scenarios with and without climate and emissions changes as specified by Wu *et al* (2008a). 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 EPPA region (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.

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.

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.

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.

Figure 2 shows an illustration of this for Asia. Panel (a) shows O₃ concentrations in Asia from Wu *et al* (2008a) in 2050 climate, with constant (year 2000) ozone precursor emissions, while panel (b) shows the changes in O₃ 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 O₃ decreases and increases, respectively, due to climatic changes. As shown in these panels, 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.

Population-weighted annual average 8-hour maximum ozone concentrations calculated from Wu *et al* (2008a) by region (ranging from 29.5 – 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 validate. We use the estimates of West *et al* (2007) (Table S.2) as a sensitivity test to assess the influence of atmospheric model and emissions scenario uncertainty on our results, discussed further below.

4. Health outcomes

Figure 3 shows the change in acute mortalities 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 acute 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 O₃ concentrations between present-day and in 2050 (panels a, b and c), and change in 2050 relative to the pre-industrial (10 ppb) level (panel c).

Overall, EPPA-HE predicts 5,000 fewer acute mortalities due to O₃ 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, high-income Asia, Canada, Europe, India, Japan, and Latin America) and net decreases in others. Detailed results for each region are presented in Table S.3.

As expected from the ozone changes (Figure 2), the increased mortality from emissions changes far outweighs the climate impact. EPPA-HE projects an increase of 817,000 acute 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. Our Monte Carlo analysis indicates a 95% confidence interval of 350,000-2,300,000 mortalities for this scenario, taking into account uncertainty in exposure-response functions. The difference in acute 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 acute mortalities, with a 95% confidence interval of 560,000-3,600,000 (Figure 3, panel d).

West *et al* (2007) previously assessed potential changes in global acute mortalities using four different scenarios. Under their MFR scenario, they calculate that emissions reductions could reduce global acute 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 exposure-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 exposure-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.

5. Economic costs of health impacts

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

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).

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. 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 4c, 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. Detailed results are presented in Table S.4.

Using EPPA-HE, we can calculate the compounding effect of ozone pollution between 2000-2049 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.

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 \$-120-170 billion.

We apply Monte Carlo analysis to assess the influence of both exposure-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% confidence interval of \$12.8 billion-\$186 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% confidence interval is \$101 billion-\$1.53 trillion. These uncertainties only take into account the uncertainties in the exposure-response factors and the economic valuation of impacts, and do not take into account additional uncertainties in future emissions and climate.

6. Policy implications and conclusions

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 3-D tropospheric chemistry simulation for the IPCC A1B scenario. We find that ozone changes due to climate and precursor emission changes lead in 2050 to 817,000 additional acute mortalities [95% confidence interval of 350,000-2,300,000], and welfare losses of \$120 billion [95% range of 12.8 billion-186 billion]; and that climate change contributes only \$790 million to the median loss. We further calculate that ozone pollution above pre-industrial background leads to >2 million [95% range of 560,000-3,600,000] acute 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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Tables and Figures

Table 1: Exposure-response functions and costs for Europe region. Sources: Bickel and Friedrich (2005); Holland *et al* (1998); Holland *et al* (2005); Matus (2005).

<i>Outcome</i>	<i>Exposure-response function¹</i>	<i>95% confidence interval²</i>	<i>Cost EU³ (\$2000)</i>	<i>Std. Error Cost⁴</i>	<i>Cost China (\$2000)</i>
Acute mortality	0.03% ⁵	(0.01%, 0.04%)	23000	3100	690
Respiratory hospital admission (adults >65 years)	1.25E-5	(-5.0E-6, 3.0E-5)	1800	570	290
Respiratory symptom day	3.3E-2	(5.7E-3, 6.3E-2)	35	11	<1
Minor restricted activity day	1.15E-2	(4.4E-3, 1.9E-2)	35	11	<1
Asthma attack	4.29E-3	(3.3E-4, 8.3E-3)	49	16	4.6
Bronchodilator usage	7.30E-2	(-2.6E-2, 1.6E-1)	0.92	0.29	<1
Lower respiratory symptoms (wheeze) in children	1.60E-2	(-4.3E-2, 8.1E-2)	35	11	<1

¹ Units are cases yr⁻¹ person⁻¹ µg⁻¹ m³

² 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.

³ Converted from €2000 using exchange rate \$1=€1.085 (mean for year 2000)

⁴ Normal distributions applied for costs.

⁵ Units are Δannual mortality rate µg⁻¹ m³

Table 2: Population-weighted ozone concentrations by EPPA region, and change in ozone due to climate, emissions, and net change 2000-2050. Ozone concentrations from Wu *et al* (2008b).

<i>Region</i>	<i>2000 [O₃]</i>	<i>2050 [O₃]</i>	<i>ΔO₃, climate</i>	<i>ΔO₃, emissions</i>	<i>ΔO₃ (2050-2000)</i>
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

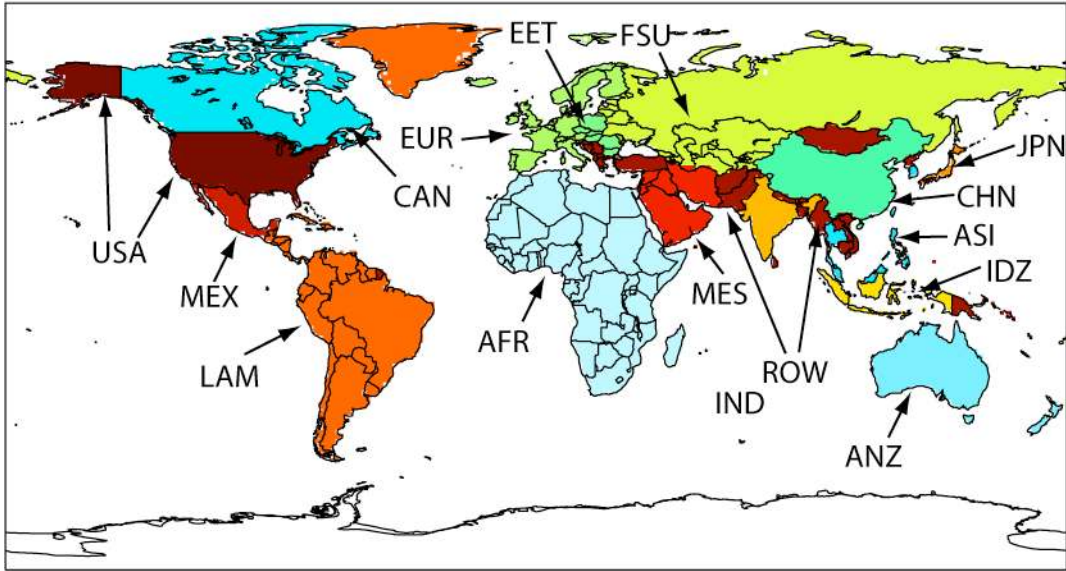


Figure 1. EPPA-HE Regions, based on EPPA4 (Paltsev *et al* 2005).

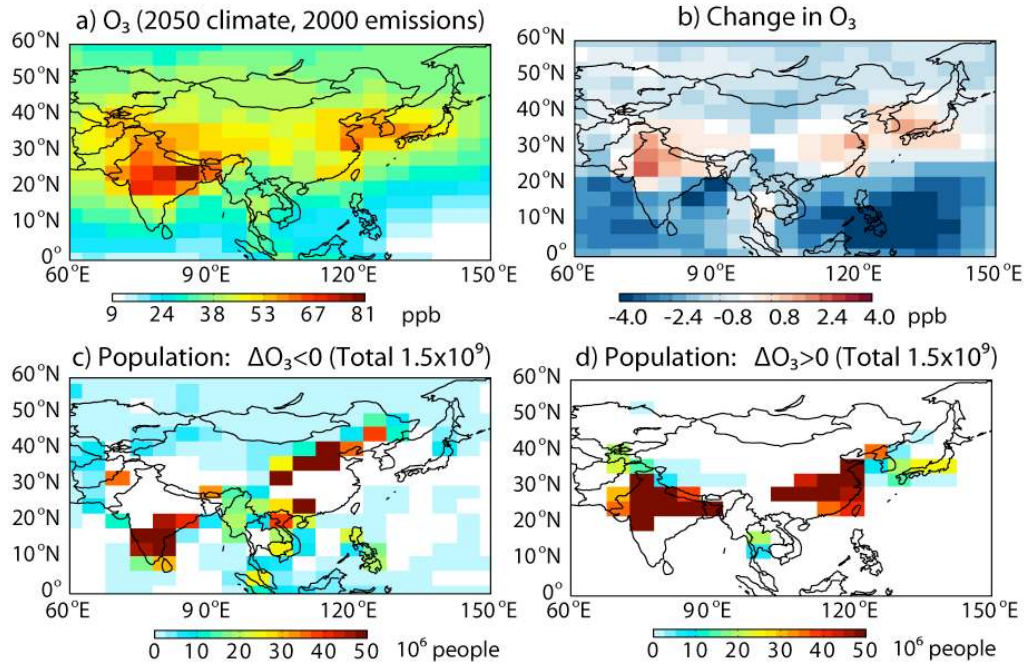


Figure 2: Model simulated O₃ change in Asia relative to population. Panel a) shows O₃ concentrations for 2050 climate and 2000 emissions (data from Wu *et al* (2008a)). Panel b) shows the overall projected change in ozone due to climate (data from Wu *et al* (2008a)). Panel c) shows total population in areas where ozone decreases due to climate, and panel d) shows total population in areas where ozone increases due to climate.

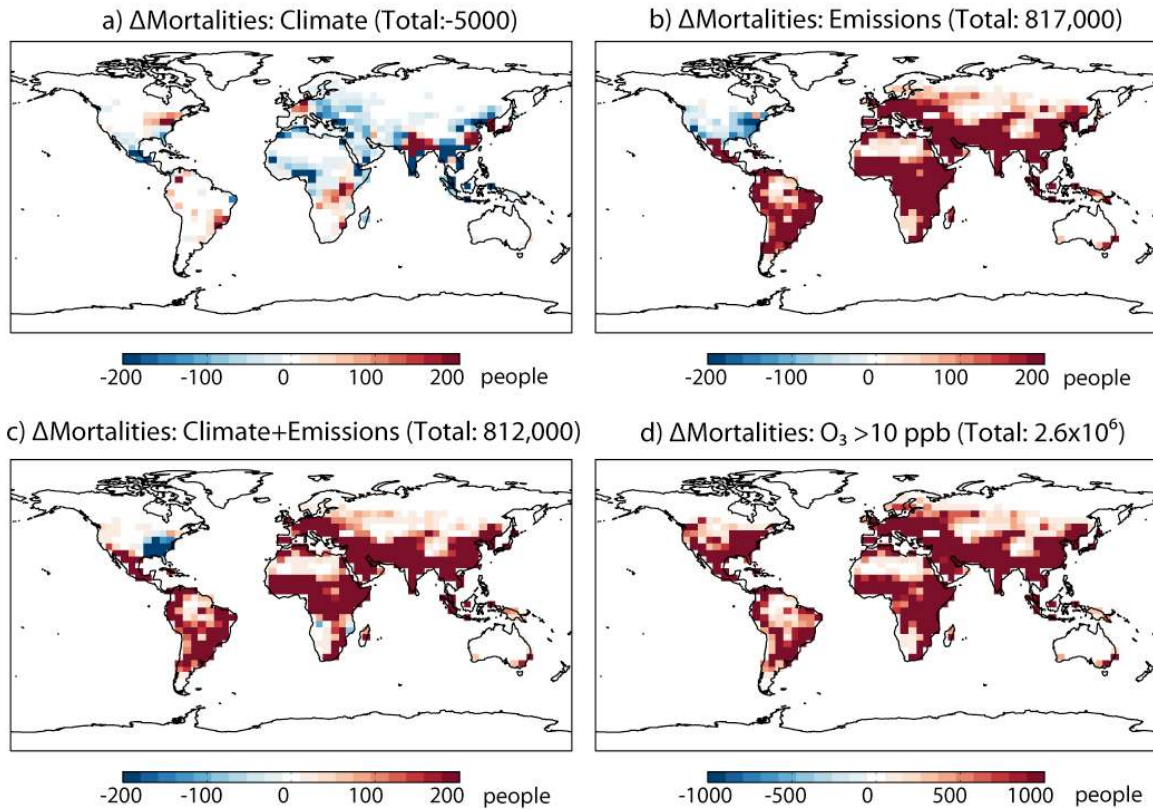


Figure 3: Change in acute mortalities due to (a) climatic change (with 2000 emissions); (b) emission changes (under 2050 climate); (c) climate and emission changes in 2050; and (d) ozone enhancements in 2050 above pre-industrial exposures (10 ppb). Acute mortality data is calculated for 16 world regions by EPPA-HE using population-weighted ozone concentrations from Wu *et al* (2008a). 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.

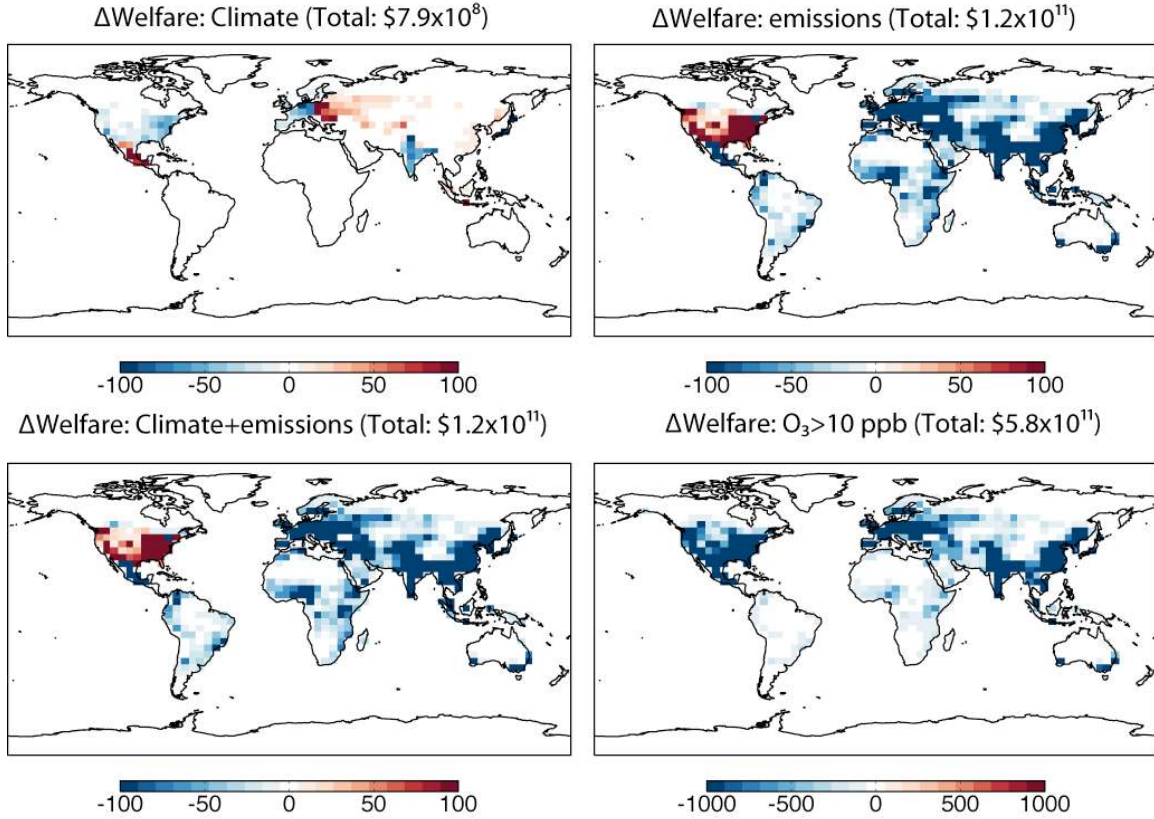


Figure 4: Change in economic welfare (consumption+leisure) from ozone-related health impacts due to (a) climatic change (with 2000 emissions); (b) emission changes (2050 climate); (c) climate and emission changes in 2050; and (d) ozone enhancements in 2050 above pre-industrial exposures (10 ppb). Welfare change is calculated for 16 world regions by EPPA-HE using population-weighted ozone concentrations from Wu *et al* (2008b). 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.

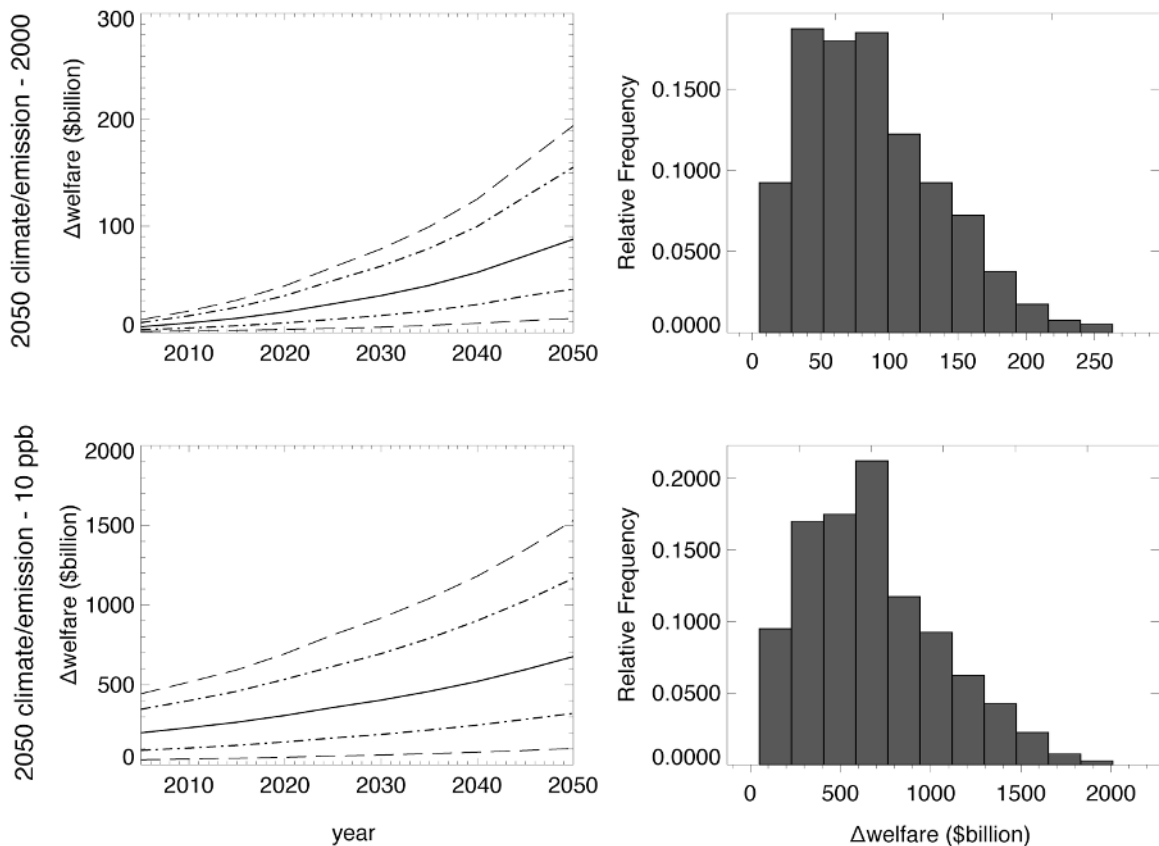


Figure 5: Uncertainty in total global loss in economic welfare (consumption+leisure) from ozone-related health impacts due to (first row) climate and emission changes in 2050 relative to 2000, and (second row) ozone enhancements in 2050 above pre-industrial exposure (10 ppb), based on a 400 sample Monte Carlo simulation. Left column shows median (solid), 67% (dash-dot) and 95% (dashed) confidence intervals. Right column shows frequency distribution of welfare loss for year 2050. All values are in year 2000\$.

References

- Bell M L, Davis D L, Cifuentes L A, Krupnick A J, Morgenstern R D and Thurston G D 2008 Ancillary human health benefits of improved air quality resulting from climate change mitigation *Environ. Health* **7** 41
- Bell M L, Goldberg R, Hogrefe C, Kinney P L, Knowlton K, Lynn B, Rosenthal J, Rosenzweig C and Patz J A 2007 Climate change, ambient ozone, and health in 50 US cities *Climatic Change* **82** 61-76
- Bell M L, Peng R D and Dominici F 2006 The exposure-response curve for ozone and risk of mortality and the adequacy of current ozone regulations *Environ. Health Persp.* **114** 532-6
- Bickel P and Friedrich R eds 2005 *ExternE--Externalities of Energy: Methodology 2005 Update* European Commission: Luxembourg
- Center for International Earth Science Information Network (CIESIN) 2005 Gridded Population of the World: Future Estimates (GPWFE). CIESIN, Columbia University, United Nations Food and Agriculture Programme (FAO), and Centro Internacional de Agricultura Tropical (CIAT). Socioeconomic Data and Applications Center (SEDAC), Columbia University: Palisades, NY
- Ebi K L and McGregor G 2008 Climate Change, Tropospheric Ozone and Particulate Matter, and Health Impacts *Environ. Health Persp.* **116** 1449
- Heston A Summers R Aten B 2002 Penn World Table Version 6.1, Center for International Comparisons at the University of Pennsylvania (CICUP) October 2002 <http://pwt.econ.upenn.edu/>.
- Hogrefe C, Lynn B, Civerolo K, Ku J Y, Rosenthal J, Rosenzweig C, Goldberg R, Gaffin S, Knowlton K and Kinney P L 2004 Simulating changes in regional air pollution over the eastern United States due to changes in global and regional climate and emissions *J. Geophys. Res.-Atmos* **109** D22301
- Holland M, Berry J and Forster D 1998 *ExternE, Externalities of Energy*, vol. 7: Methodology, 1998 update, European Commission, Directorate-General XII, Science Research and Development
- Holland M, Hurley F, Hunt A and Watkiss P 2005 *Methodology for the Cost-Benefit Analysis for CAFE: Volume 3: Uncertainty in the CAFE CBA: Methods and First Analysis* AEA Technology Environment: Didcot, UK
- Intergovernmental Panel on Climate Change (IPCC) 2001 *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* (New York: Cambridge University Press)
- Jacob D J and Winner D A 2009 Effect of climate change on air quality *Atmospheric Environment* **43** 51-63
- Knowlton K, Rosenthal J E, Hogrefe C, Lynn B, Gaffin S, Goldberg R, Rosenzweig C, Civerolo K, Ku J-Y and Kinney P L 2004 Assessing ozone-related health impacts under a changing climate *Environ. Health Persp.* **112** 1557-63
- Lopez A D, Mathers C D, Ezzati M, Jamison D T and Murray C J L eds 2006 *Global Burden of Disease and Risk Factors* Oxford University Press: New York
- Matus K 2005 Health impacts from urban air pollution in China: The burden to the economy and the benefits of policy M.S. Thesis, *Engineering Systems Division* Massachusetts Institute of Technology: Cambridge, MA
- Matus K, Yang T, Paltsev S, Reilly J and Nam K-M 2008 Toward integrated assessment of environmental change: Air pollution health effects in the USA *Climatic Change* **88** 59-92
- Mayeres I and Van Regemorter D 2008 Modelling the health related benefits of environmental policies and their feedback effects: A CGE analysis for the EU countries with GEM-E3 *Energy J.* **29** 135-50

- Mickley L J 2007 A future short of breath? Possible effects of climate change on smog
Environment **49** 34-43
- Murazaki K and Hess P 2006 How does climate change contribute to surface ozone change over the United States? *J. Geophys. Res.-Atmos.* **111** D05301
- Nam K-M, Selin N E, Reilly J M and Paltsev S 2009 Measuring Welfare Loss Caused by Air Pollution in Europe: A CGE Analysis In *MIT Joint Program on the Science and Policy of Global Change Report Series* forthcoming MIT: Cambridge, MA
- Paltsev S, Reilly J M, Jacoby H D, Eckaus R S, McFarland J, Sarofim M, Asadoorian M and Babiker M 2005 The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4 *MIT Joint Program on the Science and Policy of Global Change Report Series Report 125* MIT: Cambridge, MA
- Racherla P N and Adams P J 2006 Sensitivity of global tropospheric ozone and fine particulate matter concentrations to climate change *J. Geophys. Res.-Atmos.* **111** D24103
- Racherla P N and Adams P J 2009 US Ozone Air Quality under Changing Climate and Anthropogenic Emissions *Environmental Science & Technology* **43** 571-7
- Rind D, Lerner J, Jonas J and McLinden C 2007 Effects of resolution and model physics on tracer transports in the NASA Goddard Institute for Space Studies general circulation models *J. Geophys. Res.-Atmos.* **112** D09315
- United Nations 2007 World Population Prospects: The 2006 Revision, Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat
- Webster M, Paltsev S, Parsons J, Reilly J and Jacoby H 2008 Uncertainty in greenhouse emissions and costs of atmospheric stabilization *MIT Joint Program on the Science and Policy of Global Change Report Series Report 165* Massachusetts Institute of Technology: Cambridge, MA
- West J J, Szopa S and Hauglustaine D A 2007 Human mortality effects of future concentrations of tropospheric ozone *C. R. Geosci.* **339** 775-83
- Wu S, Mickley L J, Jacob D J, Logan J A, Yantosca R M and Rind D 2007 Why are there large differences between models in global budgets of tropospheric ozone *J. Geophys. Res.-Atmos.* **112** D05302
- Wu S L, Mickley L J, Jacob D J, Rind D and Streets D G 2008a Effects of 2000-2050 changes in climate and emissions on global tropospheric ozone and the policy-relevant background surface ozone in the United States *J. Geophys. Res.-Atmos.* **113** D18312
- Wu S L, Mickley L J, Leibensperger E M, Jacob D J, Rind D and Streets D G 2008b Effects of 2000-2050 global change on ozone air quality in the United States *J. Geophys. Res.-Atmos.* **113** D06302

Supplemental Information

Table S.1: Correlations between exposure-response functions used in uncertainty analysis.

<i>OUTCOME CORRELATION MATRIX</i>	<i>AM</i>	<i>RHA</i>	<i>RSD</i>	<i>MRD</i>	<i>AA</i>	<i>BDU</i>	<i>LRS</i>
Acute mortality (AM)	X						
Respiratory hospital admission (RHA) (adults >65 years)	0.4	X					
Respiratory symptom day (RSD)	0.4	0.4	X				
Minor restricted activity day (MRD)	0.4	0.4	0.8	X			
Asthma attack (AA)	0.4	0.4	0.8	0.8	X		
Bronchodilator usage (BDU)	0.4	0.4	0.8	0.8	0.9	X	
Lower respiratory symptoms (wheeze) in children (LRS)	0.0	0.0	0.0	0.0	0.0	0.0	X

Table S.2: Ozone concentrations (ppb) by EPPA region, based on West *et al* (2007) for sensitivity analysis. A2 refers to IPCC A2 scenario; CLE is current legislation, and MFR is maximum feasible reduction scenario.

<i>Region</i>	<i>2000</i>	<i>A2 2030</i>	<i>CLE 2030</i>	<i>MFR 2030</i>
AFR	39.3	48.5	42	36.9
ANZ	42.4	48.3	43.5	36.6
ASI	33.5	42.1	37.7	29.5
CAN	46.4	52.1	48	40.9
CHN	44.9	53	46.7	38.5
EET	41.2	47.5	43	36.9
EUR	40.4	45.1	42.2	37.3
FSU	41.2	47.5	43	36.9
IDZ	33.5	42.1	37.7	29.5
IND	45.5	60.3	54.4	39.3
JPN	42.4	48.3	43.5	36.6
LAM	35.9	44.5	36.7	31
MES	45.7	56.1	49.4	39.3
MEX	35.9	44.5	36.7	31
ROW	41.9	51.1	45.3	36.7
USA	46.4	52.1	48	40.9

Table S.3: Acute mortalities from ozone due to climate and precursor emission changes for each EPPA region.

<i>Region</i>	<i>ΔMortalities Climate</i>	<i>ΔMortalities Precursor Emissions</i>	<i>ΔMortalities Climate+ precursors</i>	<i>Excess mortalities O₃>10ppb</i>
AFR	-2640	130000	127000	391000
ANZ	-1	585	584	3980
ASI	135	44500	44600	98500
CAN	45	190	235	6810
CHN	-564	90500	89900	403000
EET	-489	1560	1070	16200
EUR	297	5210	5500	66000
FSU	-1260	4890	3630	47400
IDZ	-2140	27400	25200	61800
IND	3740	317000	321000	770000
JPN	534	1280	1820	24300
LAM	1190	46100	47300	114000
MES	-1250	33800	32600	127000
MEX	-1300	7940	6640	38000
ROW	-1360	108000	107000	362000
USA	444	-2470	-2030	79800
Total	-4640	817000	813000	2610000

Table S.4: Welfare change from ozone-related air pollution health impacts due to climate and emission changes for each EPPA region (in 10^9 year 2000\$).

<i>Region</i>	<i>ΔWelfare Climate</i>	<i>ΔWelfare Precursor Emissions</i>	<i>ΔWelfare Climate+ precursors</i>	<i>ΔWelfare (2050) $O_3 > 10ppb$</i>
AFR	0.083	-4.5	-4.4	-8.4
ANZ	0	-1.5	-1.4	-6.4
ASI	-0.012	-1.9	-2	-1.8
CAN	-0.092	-0.59	-0.47	-13
CHN	0.11	-17	-17	-57
EET	0.51	-2.2	-1.6	-14
EUR	-0.53	-9.9	-9.1	-96
FSU	1	-5.5	-4.3	-33
IDZ	0.13	-1.8	-1.7	-1.9
IND	-0.76	-56	-60	-80
JPN	-1.8	-3.6	-4.3	-73
LAM	-0.04	-1.5	-1.6	-1.9
MES	0.042	-1.6	-1.6	-4.5
MEX	1.4	-10	-8.5	-28
ROW	0.075	-6.3	-6.3	-13
USA	-0.91	2.2	4.8	-150
Total	-0.79	-120	-120	580