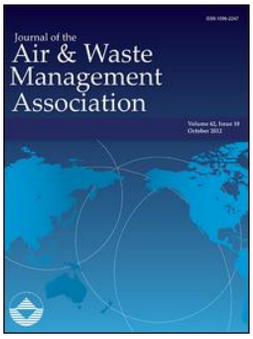

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Cost Analysis of Impacts of Climate Change on Regional Air Quality

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ABSTRACT

Climate change has been predicted to adversely impact regional air quality with resulting health effects. Here a regional air quality model and a technology analysis tool are used to assess the additional emission reductions required and associated costs to offset impacts of climate change on air quality. Analysis is done for six regions and five major cities in the continental United States. Future climate is taken from a global climate model simulation for 2049–2051 using the Intergovernmental Panel on Climate Change (IPCC) A1B emission scenario, and emission inventories are the same as current ones to assess impacts of climate change alone on air quality and control expenses. On the basis of the IPCC A1B emission scenario and current control technologies, least-cost sets of emission reductions for simultaneously offsetting impacts of climate change on regionally averaged 4th highest daily maximum 8-hr average ozone and yearly averaged $PM_{2.5}$ (particulate matter [PM] with an aerodynamic diameter less than 2.5 μm) for the six regions examined are predicted to range from \$36 million (1999\$) yr^{-1} in the Southeast to \$5.5 billion yr^{-1} in the Northeast. However, control costs to offset climate-related pollutant increases in urban areas can be greater than the regional costs because of the locally exacerbated ozone levels. An annual cost of \$4.1 billion is required for offsetting climate-induced air quality impairment in 2049–2051 in the five cities alone. Overall, an annual cost of \$9.3 billion is estimated for offsetting climate change impacts on air quality for the six regions and five cities examined. Much of the additional expense is to reduce increased levels of ozone. Additional control costs for offsetting the impacts everywhere in the United States could be larger than the estimates in this study. This study shows that additional emission controls and associated costs for offsetting climate impacts could significantly increase currently estimated control requirements and should be considered in developing control strategies for achieving air quality targets in the future.

IMPLICATIONS

Future climate change may increase regional air pollutant levels because of its influence on photochemical reactions, precursor emissions, and meteorological conditions. Additional emission controls for offsetting effects of climate change penalties on regional air quality could increase the costs for achieving planned air quality targets in the future. The effects of climate change should be considered in control strategy development as well as in cost-and-benefit analysis for future attainment of air quality standards.

INTRODUCTION

Climate change has been forecast to influence ground-level ozone (O_3) and particulate matter (PM) levels by affecting meteorological conditions, biogenic precursor emissions, photochemical reactions, and thermodynamic equilibriums.[1–4] More volatile organic compound (VOC) emissions, especially from biogenic sources, increase peak O_3 concentrations in VOC-limited urban areas. Some studies also show that higher temperatures, faster photochemical rates, and more stagnant climate conditions accelerate ground-level O_3 formation.[1,3] $PM_{2.5}$ (PM with an aerodynamic diameter <2.5 μm) concentrations also change in response to modifications in emissions, stagnation, precipitation, rates of photochemical reactions, and shifts of thermodynamic equilibriums between gas- and condense-phase semi-volatile compounds.[2,4] Overall, climate-induced changes in air quality are expected to exacerbate adverse health effects, including increases in mortality rate and respiratory illness due to elevated O_3 and $PM_{2.5}$ levels.[5,6]

To mitigate the adverse effects induced by climate change, air quality managers should take into account

potential increases in control costs for achieving air quality standards under impacts of climate change. Furthermore, such costs should be considered in the overall costs of possible impacts of global climate change. The objective of this study is to estimate the additional reductions in precursor emissions required and associated costs for offsetting the climate change penalty on regional air quality. Here the results of a regional air quality model are used to investigate the impacts of climate change on future air quality, and a technology analysis tool is used to estimate associated costs of emission reductions for offsetting those impacts for six regions and five large urban areas in the continental United States. The future climate scenario is from a global climate model (GCM) simulation using the Intergovernmental Panel on Climate Change (IPCC) A1B emission scenario, which assumes a future world of rapid economic growth with a balance between fossil and non-fossil energy sources and projects mid-level increases in greenhouse gas emissions within the six IPCC Special Report on Emission Scenarios (SREs) (B1, A1T, B2, A1B, A2, and A1F1).[7,8] The authors consider the resulting changes in ground-level O_3 and $PM_{2.5}$ as both causing adverse health effects,[9,10] and several urban areas violate current National Ambient Air Quality Standards (http://www.epa.gov/air/criteria.html) for those two pollutants. Climate-induced changes on biogenic and anthropogenic emissions and air pollutant levels may have positive or negative feedbacks on climate change. Those feedbacks are uncertain because of complicated mechanisms and therefore are not included in the IPCC emission scenarios[7,8] or the assessments in this study. Uncertainties in climate-induced changes in anthropogenic emissions could induce slight underestimates in the effects of climate penalty on air quality and associated costs for offsetting those effects because a hotter climate could lead to a higher demand of electricity and eventually lead to more air pollutant emissions (e.g., oxides of nitrogen [NO_x] and sulfur dioxide [SO_2]). However, those feedbacks are expected to be small because those anthropogenic air pollutants are not significant greenhouse gases and controls in place by 2050 are expected to reduce SO_2 emissions and the resulting sulfate formation.

METHODS

Regional Air Quality Modeling

Details of the air quality modeling approach are given elsewhere[4,11] and summarized here. The U.S. Environmental Protection Agency (EPA)'s Models-3 Air Quality Modeling System—Fifth-Generation NCAR/Penn State Mesoscale Model (MM5), the Sparse Matrix Operator Kernel Emissions (SMOKE), and Community Multiscale Air Quality Model (CMAQ)—is used for investigating the impacts of climate change on air quality. MM5[12,13] is used to downscale the National Aeronautics and Space Administration (NASA)'s Goddard Institute of Space Studies (GISS)[14] results for the years 2000–2002 and 2049–2051 assuming climate change following the IPCC A1B emission scenario.[15,16] 2049–2051 is chosen as a compromise between time scales with nontrivial climate change and still within a reasonable time scale for policy-making in regards to long-term air quality planning and greenhouse gas reductions (http://www.epa.gov/climatechange/downloads/s2191_EPA_Analysis.pdf), which are expected to affect regional air quality (i.e., O_3 and $PM_{2.5}$). Emissions for current (2000–2002) and future (2049–2051) episodes are processed using the SMOKE modeling system (http://www.smoke-model.org/index.cfm). To assess the impacts of climate change alone, the emission inventories used for 2049–2051 are the same as 2000–2002. However, biogenic and anthropogenic emissions (e.g., biogenic VOC and mobile evaporative NO_x) respond to changes in meteorological conditions, particularly temperature, and those effects on emissions are included.

CMAQ version 4.3[17] and the decoupled direct method 3D (DDM-3D)[18–20] are used to simulate O_3 and $PM_{2.5}$ concentrations and quantify their sensitivities to emissions. DDM-3D uses a first-order Taylor Series approximation and directly calculates the linearized local sensitivities of pollutants to precursor emissions; that is, the linearized (first-order) sensitivity ($S_{i,j}$) of pollutant concentration i (C_i) to source emissions j (E_j) is calculated as

$$S_{i,j} = E_j \frac{\partial C_i}{\partial E_j} \tag{1}$$

The linearized local sensitivities have the same units as the corresponding pollutants. Near linearity to emission changes has been shown for changes on the order of up to 30–50% in the southeastern United States.[21,22] The linear approximation could induce a bias in estimating how air pollutants respond to emissions,[23] but the bias is expected to be small if emissions are not significantly changed (e.g., <30–50%).

Because air pollutants and their precursors can originate from sources located across broad geographic areas, air quality control strategies should be designed from a regional perspective. In this study, the continental United States is divided into six regions—West, Central, Great Lakes, Northeast, Mid-Atlantic, and Southeast (Figure 1). This division of regions is consistent with an emission control analysis tool, AirControlNET,[24] which is used in this study and includes broad sources of regional assignments; for example, Regional Planning Organizations (RPOs) (http://www.epa.gov/visibility/regional.html), the Ozone Transport Commission (OTC) (http://www.otcair.org), North American Electric Reliability Council (NERC) Regions (http://www.nerc.com), and others. Analyses of regional average values can be compared with current control strategies made from a regional perspective; for example, cap-and-trade programs for acid rain in the eastern United States. On the other hand, such a perspective is less relevant for considering local attainment. As such, this study specifically considers attainment issues in cities that are expected to require the greatest additional controls to overcome the impacts of the climate penalty on air quality.[25] In addition to those six regions, air quality impacts in five metropolitan areas in the continental United States—Atlanta, Chicago, Houston, Los Angeles, and New York—were also investigated in this study because each currently experiences high O_3 and $PM_{2.5}$ levels (http://www.epa.gov/oar/oaqps/greenbk). These five cities represent those likely needing the greatest level of emission reductions to reach the O_3 and

Figure 1. Simulation domain, including six U.S. regions and five cities.

$PM_{2.5}$ standards. Prior studies show that impacts of precursor emissions on air quality drop quickly with increasing distance between receptors and emission sources,[26] so controls in or near the cities will be most influential on a per mass basis. In the city-specific analyses, emission controls within its metropolitan statistical area (MSA; for definition of MSA, see http://www.whitehouse.gov/omb/bulletins/fy2007/b07-01.pdf) are considered. Emission reductions at the MSA level may be politically easier to enact and enforce and more effective (e.g., on a per ton of emissions reduced basis) for improving air quality in the cities than regional controls, although regional controls have broader benefits and may be more economically effective when considering the more widespread reductions. The authors have chosen to consider regional reductions and MSA-focused reductions. In the ensuing analysis, benefits of controls in one region are not included for regions downwind, recognizing that the emissions impacts are felt most strongly in the state of origin or in an adjacent state.[27–29] This can induce overestimates in the calculated costs in the analysis because it limits the possibility of emission reductions from other areas that could reduce air pollutant levels in the cities.

Similar to the form of the applicable regulatory standards, yearly averaged $PM_{2.5}$ concentrations in 2001 and 2050 are simulated, along with summer (June, July, and August) 4th highest daily maximum 8-hr average O_3 (4th MDA8hr O_3) in 2000–2002 and 2049–2051. For the five cities examined, yearly averaged concentrations and sensitivities of $PM_{2.5}$ are calculated at the city centers of the five cities whereas summertime regional maximum 4th MDA8hr O_3 (i.e., the highest 4th MDA8hr O_3 among 5-by-5 grid cells around the city center [36 km on edge each], Figure 1) is investigated because O_3 levels peak in the summer and downwind of city centers. Simulated and observed interannual variability of meteorology has been assessed by Tagaris et al.,[4] and the results show that the cumulative distribution function (CDF) and spatial distribution plots for meteorological fields are similar for the 3 consecutive years in the future (2049–2051). Therefore, more consecutive years of simulations are not expected to significantly affect the results shown in the study.

Development of Cost Functions for Emission Reductions

Here, the EPA's control technology analysis tool, AirControlNET version 4.1,[24] is used to estimate the costs of emission reductions of major O_3 and $PM_{2.5}$ precursors: anthropogenic SO_2, NO_x, and VOCs, for the six regions and five cities in the United States. Because most of the $PM_{2.5}$ is secondary (Figure S1, published at http://secure.awma.org/onlinelibrary/samples/10.3155-1047-3289.60.2.195_supplmaterial.pdf), control costs of primary PM are not included in this study. AirControlNET uses EPA's 1999 National Emission Inventory (NEI) as a source of emission data (http://www.epa.gov/ttn/chief/net/1999inventory.html) linked to a database of emission control measures of applicability, efficiency, and cost information by Cost POD. This is a group of source types, as defined by Source Classification Codes (SCCs), that have similar emission characteristics, control techniques, and control costs. AirControlNET provides the mass of emissions reduced from current total controllable emissions (i.e., both currently controlled and uncontrolled emissions) and associated annual costs for emission control measures (by species, state, cost per ton, etc.) including annualized capital costs and yearly operation and maintenance (O&M) costs. The annualized capital costs were calculated by taking into account interest rates, lifetime of the emission control equipments, and capital recovery factors.[24] The results of AirControlNET could also be applied to estimate the implementation costs of current market-based control strategies. Costs of emission reductions in the future are presented in 1999$ to compare with currently estimated costs of emission reductions for improving regional air quality in the United States. Reductions in anthropogenic precursor emissions and their associated costs do not increase linearly: higher reductions in amount of emissions are expected to be more expensive based on per unit reduction.[30,31] Here, costs of emission reductions calculated by AirControlNET are fit to a second-order polynomial, exponential, or power function of absolute amount of emission reductions depending on species and region (Figure 2 and supplemental data Figures S2–S6). Each point in each figure was selected based on criteria of the cost per ton

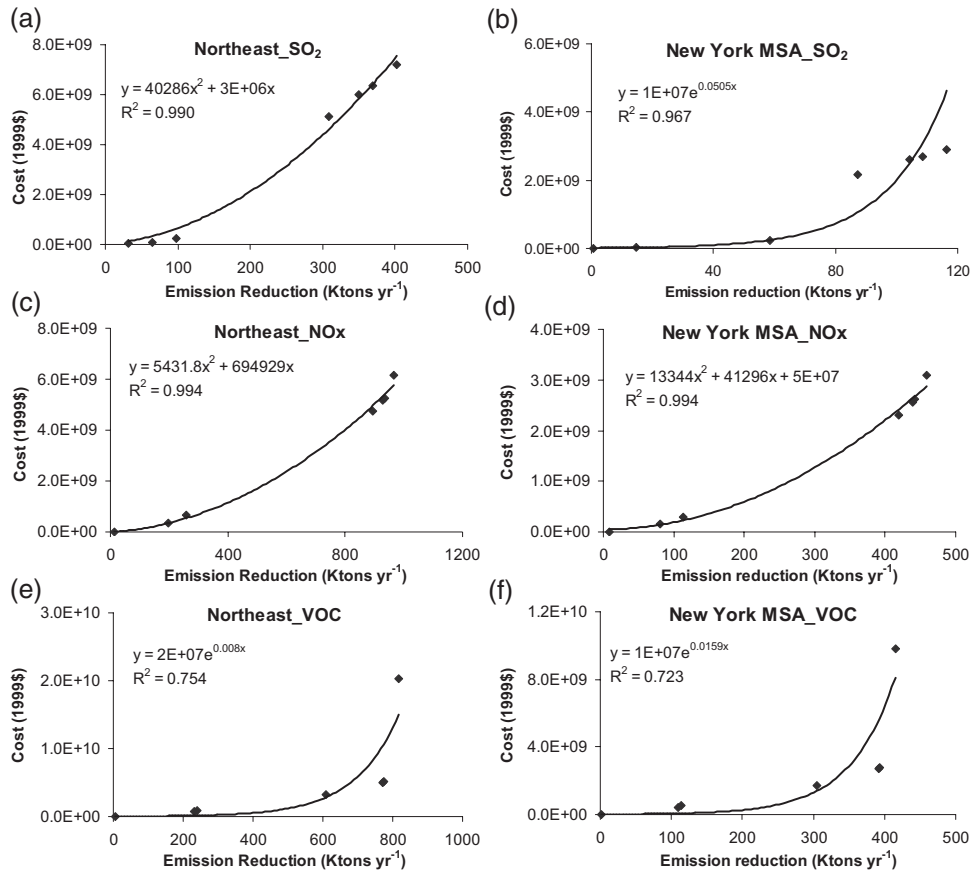

Figure 2. Relationship between costs and amount of emission reductions in anthropogenic SO_2, NO_x, and VOC emissions for (a, c, e) the Northeast and (b, d, f) New York MSA (cost functions for the other regions and MSAs of cities are presented in supplemental data).

of pollutant emission reductions, which range from less than \$1,000/t to more than \$20,000/t. Emission controls chosen to reduce one species sometimes impact emissions of other species from same sources (e.g., using cleaner fuels alter NO_x, VOC, and PM emissions from mobile sources). However, use of the curve fits with limited sample size and degrees of freedom does not allow for directly assessing the synergy of the simultaneous emission reductions for multiple precursors. For each of the regions and cities, the total costs for offsetting impacts of climate change on O_3 and $PM_{2.5}$ levels are a summation of the costs of reductions in anthropogenic SO_2, NO_x, and VOC emissions. Given that the analysis does not account for combined benefits of emission controls and does not include primary $PM_{2.5}$ controls, there is a potential high bias in the study for higher calculated costs. However, primary $PM_{2.5}$ is a relatively small fraction of total $PM_{2.5}$, and the most cost-effective approaches to reduce $PM_{2.5}$ tend to be reductions in gaseous precursors (e.g., SO_2), and, as found in this study, costs to overcome the climate penalty are largely driven by reducing O_3. Further, primary $PM_{2.5}$ levels are not significantly affected by climate change. Control technology advancements should lead emission reductions to be more cost-effective, and renewable energy sources also have the potential to reduce emissions. The extent of these possibilities is quite uncertain and is not included in the development of cost functions. Costs of per unit emission reductions and maximum control efficiencies are taken as those provided by AirControlNET for current applications. Using a dataset relying on current control technologies and energy sources could introduce overestimates in the calculated costs when applied to the future.

To offset changes in 4th MDA8hr O_3 and yearly averaged $PM_{2.5}$ induced by climate change, the differences between future and present day concentrations of each pollutant (i.e., $\overline{C}_{p,2050s} - \overline{C}_{p,2001s}$ in eq 2) must be less than or equal to the decreases in pollutant levels from emission reductions estimated by the authors' sensitivity analysis; that is, the following equation should be satisfied for each of the cities and regions:

$$\sum_{k} \Delta\varepsilon_k S_{pk} \geq \bar{C}_{p,2050s} - \bar{C}_{p,2001s} \qquad (2)$$

where $\Delta\varepsilon_k$ is the reduction ratio of species k; S_{pk} is the sensitivity of pollutant p to species k; $\overline{C}_{p,2050s}$ and $\overline{C}_{p,2001s}$ are the concentrations of pollutant p in 2049–2051 and 2000–2002, respectively; k is the anthropogenic SO_2, NO_x, and VOC; and p is the summertime 4th MDA8hr O_3 and yearly averaged $PM_{2.5}$.

Sensitivities of the three-summer average regional maximum 4th MDA8hr O_3 to anthropogenic NO_x and VOC emissions as well as yearly averaged $PM_{2.5}$ to anthropogenic SO_2, NO_x, and VOC emissions are used in eq 2 to calculate the amount of emission reductions required for

offsetting effects of climate change on air quality in 2049–2051 on the basis of the least-cost set of controls. The least-cost sets of emission reductions are found among all of the possible emission control approaches using the cost functions developed from AirControlNET outputs and eq 2. Details of development of least-cost control strategies are provided in the supplemental data.

RESULTS AND DISCUSSION

Effects of Climate Change on Regionally Averaged and Urban O_3 and $PM_{2.5}$ Levels

Regionally averaged summer 4th MDA8hr O_3 concentrations range from approximately 64 (West) to 90 parts per billion by volume (ppbv) (Southeast) for the six regions in 2000–2002 and an increase of up to 4.8 ppbv is predicted in 2049–2051 summers compared with 2000–2002 summers when keeping the emission inventory constant (Table 1). Simulated yearly averaged $PM_{2.5}$ concentrations range from 4.4 to 12.4 $\mu g\ m^{-3}$ in 2001 on a regional basis. When the emission inventory is kept constant, between 2001 and 2050, $PM_{2.5}$ concentrations are predicted to increase in 2050 in the Great Lakes, Mid-Atlantic, Northeast and West regions, and the largest climate-induced increases in regional yearly averaged $PM_{2.5}$ concentrations are predicted to be 0.8 $\mu g\ m^{-3}$ (Northeast) (Table 2). Detailed discussion of pollutant responses to climate change is presented elsewhere.[1–4] Evaluations of predicted regionally averaged O_3 and $PM_{2.5}$ levels for 2000–2002 are presented in Tagaris et al.,[4] and results show that summer maximum 8-hr average O_3 (M8hrO_3) levels were overestimated by 15%, whereas $PM_{2.5}$ levels were underestimated by approximately 30% in 2000–2002 for the continental United States because CMAQ does not fully capture secondary organic aerosol (SOA) formation and low organic carbon has been noted.[32]

For urban air quality, the model tends to overestimate summer M8hrO_3 concentrations in 2001 for the cities examined here (Atlanta ~35%, Chicago ~55%, Houston ~15%, Los Angeles ~5%, and New York ~15%). $PM_{2.5}$ concentrations are overpredicted in the five cities except Chicago (~ −1%). For the five U.S. cities studied, average simulated concentrations of the regional maximum 4th MDA8hr O_3 range from approximately 96 (New York) to 114 ppbv (Atlanta) in 2000–2002 summers. The three-summer average regional maximum 4th MDA8hr O_3 concentrations are predicted to increase up to 17.7 ppbv (Los Angeles) in 2049–2051 compared with 2000–2002 for the cities examined, although the 4th MDA8hr O_3 in Chicago is simulated to decrease because of increases in cloud cover in the 2050s in the Midwest[16] (Table 1). Increases in peak O_3 concentrations are attributed to higher temperatures and more severe stagnation. Yearly averaged $PM_{2.5}$ concentrations are simulated to range from 12.7 to 19.7 $\mu g\ m^{-3}$ for the five cities in 2001 (Table 2). Urban $PM_{2.5}$ concentrations are predicted to increase in Chicago, Los Angeles, and New York but decrease slightly in Atlanta and Houston in 2050 as compared with 2001 (Table 2). The largest climate-induced increases in urban yearly averaged $PM_{2.5}$ concentrations are predicted to be 2 $\mu g\ m^{-3}$ in Chicago. Chemical composition of the yearly averaged urban $PM_{2.5}$ is predicted to change slightly (Figure S1 in supplemental data). Higher temperatures and stronger radiation in the projected climate accelerate SO_2 oxidation, forming slightly more sulfate, whereas increases in temperature and less ammonia being available favor nitrate existing in the gas phase and decrease the amount nitrate in $PM_{2.5}$. Overall, results show that regionally averaged and urban $PM_{2.5}$ levels are more sensitive to reductions in anthropogenic SO_2 and NO_x emissions than anthropogenic VOC emissions (Table 2).

Least-Cost Emission Controls for Offsetting Impacts of Climate Change on Regionally Averaged Air Quality

Costs of simultaneously offsetting impacts of climate change on regionally averaged 4th MDA8hr O_3 and $PM_{2.5}$ concentrations in 2049–2051 summers are predicted to range from about \$36 million yr^{-1} (1999\$) (Southeast) to \$5.5 billion yr^{-1} (Northeast) for the six regions examined on the basis of the least-cost approach (Table 3). Required reductions in anthropogenic SO_2, NO_x, and VOC emissions from the Northeast region are calculated to be 32, 50, and 13%, respectively. Because annual incremental emission reductions and costs from 2000–2002 to 2049–2051 were not investigated, there is no specific time frame for implementation of additional emission reductions. However, 2049–2051 should be included in the time frame of emission

Table 1. Regional 4th MDA8hr O_3 in 2000–2002 and 2049–2051 summers as well as sensitivity of 4th MDA8hr O_3 to anthropogenic NO_x ($S_{4th\ MDA8\ h\ O3,NOx}$) and VOC ($S_{4th\ MDA8\ h\ O3,VOC}$) emissions in 2049–2051 summers for the six regions and five cities in the United States (values in ppbv).

Region/City	2000–2002 Summer Concentration	2049–2051 Summer Concentration	ΔConcentration (2050–2001)	2049–2051 Summer $S_{O3,ANOx}$	2049–2051 Summer $S_{O3,AVOC}$
Central[a]/Houston	82.5/105.9	82.9/112.2	0.4/6.3	27.9/38.2	1.7/4.5
Great Lakes[b]/Chicago	86.2/112.8	86.4/109.4	0.2/−3.4	27.1/35.0	2.7/4.7
Northeast[c]/New York	69.6/95.8	74.4/106.9	4.8/11.1	23.1/18.6	2.2/10.6
Southeast[d]/Atlanta	90.1/113.9	90.9/123.4	0.8/9.5	33.9/51.9	1.8/2.2
West[e]/Los Angeles	63.6/102.1	64.6/119.8	1.0/17.7	15.9/8.5	1.3/23.1
Mid-Atlantic[f]	89.2	93.0	3.8	32.8	2.2

Notes: [a]Central = Arkansas, Iowa, Kansas, Louisiana, Minnesota, Missouri, Nebraska, Oklahoma, and Texas; [b]Great Lakes = Illinois, Indiana, Michigan, Wisconsin, and Ohio; [c]Northeast = Connecticut, Maine, Massachusetts, New Hampshire, New York, Rhode Island, and Vermont; [d]Southeast = Alabama, Florida, Georgia, Kentucky, Mississippi, North Carolina, South Carolina, and Tennessee; [e]West = Arizona, California, Colorado, Idaho, Montana, New Mexico, North Dakota, Oregon, South Dakota, Utah, Washington, Wyoming, and Nevada; [f]Mid-Atlantic = Delaware, District of Columbia, Maryland, New Jersey, Pennsylvania, Virginia, and West Virginia.

Table 2. Yearly $PM_{2.5}$ concentrations in 2001 and 2050 and sensitivity of $PM_{2.5}$ to anthropogenic SO_2 ($S_{PM2.5,SO2}$), NO_x ($S_{PM2.5,NOx}$), and VOC ($S_{PM2.5,VOC}$) emissions in 2050 for the six regions and five cities in the United States (values in $\mu g\ m^{-3}$).

Region/City	2001 Concentrations	2050 Concentrations	ΔConcentrations (2050–2001)	2050 $S_{PM2.5,SO2}$	2050 $S_{PM2.5,ANOx}$	2050 $S_{PM2.5,AVOC}$
Central/Houston	10.2/16.5	10.0/16.0	−0.2/−0.5	2.2/3.4	1.7/1.7	−0.1/0.0
Great Lakes/Chicago	11.8/19.0	12.5/21.0	0.7/2.0	2.0/2.4	1.8/3.1	0.1/0.3
Northeast/New York	7.1/19.7	7.9/21.2	0.8/1.5	1.2/2.2	0.8/2.1	0.1/0.5
Southeast/Atlanta	12.4/19.7	12.0/19.0	−0.4/−0.7	3.0/3.4	1.5/2.1	0.0/0.2
West/Los Angeles	4.4/12.7	4.6/12.8	0.2/0.1	0.6/0.4	0.6/0.6	0.0/0.1
Mid-Atlantic	11.3	11.6	0.3	2.4	1.0	0.2

reductions for the purpose of offsetting climate change effects on air quality then. The high costs of emission reductions for offsetting impacts of climate change on regionally averaged air quality in the Northeast are mainly attributed to offsetting the significant increases in 4th MDA8hr O_3 (4.8 ppbv) in 2049–2051 summers compared with 2000–2002 summers. Reductions in anthropogenic NO_x and VOC emissions are predicted to decrease summer 4th MDA8hr O_3 and yearly averaged $PM_{2.5}$ levels because sensitivities of both pollutants to anthropogenic NO_x and VOC emissions are positive. Although the reductions in anthropogenic NO_x and VOC emissions reduce $PM_{2.5}$, approximately 32% reductions in SO_2 emissions from the Northeast are required to help offset the 0.8-$\mu g\ m^{-3}$ increase in yearly averaged $PM_{2.5}$ levels.

Reductions of 24% in SO_2 and 12% in NO_x emissions for the Great Lakes region are required to offset increases in O_3 and $PM_{2.5}$ levels (Table 3). The 12% reduction in anthropogenic NO_x emissions decreases O_3 and $PM_{2.5}$ levels, whereas the 24% reductions in SO_2 emissions address $PM_{2.5}$ levels. Reductions in VOC emissions are not predicted to be cost-effective because regional sensitivities of $PM_{2.5}$ to anthropogenic VOC emissions are small (Table 2). Overall, the least-cost solution for offsetting impacts of climate change on O_3 and $PM_{2.5}$ levels is predicted to be \$579 million yr^{-1}. For the West, reductions in anthropogenic SO_2 and NO_x emissions for offsetting impacts of climate change on O_3 and $PM_{2.5}$ are predicted to be approximately 17 and 6%, respectively. The least-cost emission reductions for offsetting impacts of climate change on air quality are calculated to be approximately \$286 million yr^{-1} in the West. Reductions of 9% in SO_2 and 13% in NO_x emissions are required for offsetting climate effects on air quality in the Mid-Atlantic region, and the associated cost is predicted to be \$210 million yr^{-1} (Table 3).

Impacts of future climate change on air quality are predicted to require only modest costs for additional emission controls in the Southeast and Central regions: 2.4 and 2.8% reductions in anthropogenic NO_x emissions are suggested (Table 3), respectively, because climate change causes slight increases in summer 4th MDA8hr O_3 and decreases in yearly averaged $PM_{2.5}$ levels in both regions (Tables 1 and 2). The associated costs of emission reductions are predicted to be \$36 and \$115 million yr^{-1} for the Southeast and Central regions, respectively. Overall, the total annual costs for offsetting climate impacts on

Table 3. Percentage (%) and amount (kt) of emissions reductions from the six regions and MSAs of the five cities, as well as associated annual costs (1999\$) for offsetting impacts of climate change on 4th MDA8hr O_3 and $PM_{2.5}$ in 2049–2051.

Region/City	SO_2 Reduction (%)	NO_x Reduction (%)	VOC Reduction (%)	SO_2 Reduction (kt)	NO_x Reduction (kt)	VOC Reduction (kt)	Annual Cost (millions of 1999\$)
Central[a]/Houston[g]	~0/~0	2.8/16.5	~0/~0	~0/~0	150/63	~0/~0	\$115/\$48
Great Lakes[b]/Chicago[h]	24.0/52.3	11.9/22.6	~0/14.4	858/129	431/118	~0/47	\$579/\$292
Northeast[c]/New York[i]	32.1/24.2	50.2/38.8	13.1/36.7	228/30	628/241	209/203	\$5,470/\$1,132
Southeast[d]/Atlanta[j]	~0/~0	2.4/18.0	~0/7.5	~0/~0	107/55	~0/13	\$36/\$49
West[e]/Los Angeles[k]	17.3/~0	6.3/47.5	~0/59.2	186/~0	240/263	~0/199	\$286/\$2,614
Mid-Atlantic[f]/–	8.6/–	12.8/–	~0/–	216/–	298/–	~0/–	\$210/–
Total	–	–	–	1488/159	1854/740	209/462	\$6,696/\$4,135

Notes: Maximum controllable emissions and maximum removal efficiencies of SO_2, NO_x, and VOCs; both are calculated in 1999 levels. [a]Central: SO_2 = 2640 kt yr^{-1}, NO_x = 5362 kt yr^{-1}, VOCs = 3491 kt yr^{-1}; maximum control efficiencies: SO_2 = 0.833, NO_x = 0.724, VOCs = 0.772. [b]Great Lakes: SO_2 = 3573 kt yr^{-1}, NO_x = 3620 kt yr^{-1}, VOCs = 2605 kt yr^{-1}; maximum control efficiencies: SO_2 = 0.943, NO_x = 0.777, VOCs = 0.801. [c]Northeast: SO_2 = 710 kt yr^{-1}, NO_x = 1250 kt yr^{-1}, VOCs = 1593 kt yr^{-1}; maximum control efficiencies: SO_2 = 0.920, NO_x = 0.891, VOCs = 0.878. [d]Southeast: SO_2 = 3941 kt yr^{-1}, NO_x = 4473 kt yr^{-1}, VOCs = 4184 kt yr^{-1}; maximum control efficiencies: SO_2 = 0.967, NO_x = 0.867, VOCs = 0.955. [e]West: SO_2 = 1076 kt yr^{-1}, NO_x = 3812 kt yr^{-1}, VOCs = 3646 kt yr^{-1}; maximum control efficiencies: SO_2 = 0.863, NO_x = 0.745, VOCs = 0.774. [f]Mid-Atlantic: SO_2 = 2528 kt yr^{-1}, NO_x = 2329 kt yr^{-1}, VOCs = 1746 kt yr^{-1}; maximum control efficiencies: SO_2 = 0.855, NO_x = 0.908, VOCs = 0.968. [g]Atlanta MSA maximum controllable emissions: SO_2 = 290 kt yr^{-1}, NO_x = 307 kt yr^{-1}, VOCs = 171 kt yr^{-1}; maximum control efficiencies: SO_2 = 0.935, NO_x = 0.737, VOCs = 0.752. [h]Chicago MSA maximum controllable emissions: SO_2 = 247 kt yr^{-1}, NO_x = 522 kt yr^{-1}, VOCs = 326 kt yr^{-1}; maximum control efficiencies: SO_2 = 0.893, NO_x = 0.686, VOCs = 0.778. [i]Houston MSA maximum controllable emissions: SO_2 = 105 kt yr^{-1}, NO_x = 383 kt yr^{-1}, VOCs = 161 kt yr^{-1}; maximum control efficiencies: SO_2 = 0.885, NO_x = 0.780, VOCs = 0.731. [j]Los Angeles MSA maximum controllable emissions: SO_2 = 17 kt yr^{-1}, NO_x = 554 kt yr^{-1}, VOCs = 336 kt yr^{-1}; maximum control efficiencies: SO_2 = 0.909, NO_x = 0.811, VOCs = 0.753. [k]New York MSA maximum controllable emissions: SO_2 = 125 kt yr^{-1}, NO_x = 622 kt yr^{-1}, VOCs = 552 kt yr^{-1}; maximum control efficiencies: SO_2 = 0.935, NO_x = 0.737, VOCs = 0.752.

air quality in 2050 for all of the six regions are calculated to be \$6.7 billion (Table 3); such costs are mainly attributed to combating significant increases in future summer 4th MDA8hr O_3 levels in the Northeast region. However, this analysis does not consider how controls of precursor emissions in one region impact air quality domainwide and could lead to a small overestimation on the calculated costs.

Least-Cost Emission Controls for Offsetting Impacts of Climate Change on Urban Air Quality

Costs of offsetting the impacts of climate changes on air quality in 2049–2051 are predicted to range from \$48 million yr^{-1} (Houston) to \$2.6 billion yr^{-1} (Los Angeles) for the five U.S. cities examined (Table 3). The high costs in Los Angeles are attributed to significant reductions in anthropogenic NO_x (~48%) and VOC (~59%) emissions mainly for offsetting increased O_3 levels. Such significant emission reductions are likely beyond the range of the linear approximation of the sensitivities and are expected to induce a small bias in the costs because of nonlinear responses of O_3 to emission changes. The costs of offsetting climate impacts on O_3 and $PM_{2.5}$ in Los Angeles are much larger than those in the region where it is located (West) (\$286 million yr^{-1}) because climate change is predicted to significantly increase summer O_3 in Los Angeles (17.7 ppbv), but climate impacts on regionally averaged O_3 (1 ppbv) and $PM_{2.5}$ (0.2 $\mu g\ m^{-3}$) in the West region are modest. Reductions in anthropogenic SO_2, NO_x, and VOC emissions of approximately 24, 39, and 37%, respectively, from the New York MSA are required for offsetting the significant increases in the concentrations of 4th MDA8hr O_3 (11.1 ppbv) and $PM_{2.5}$ (1.5 $\mu g\ m^{-3}$) attributed to climate change. The associated least-cost set of additional controls is calculated to be about \$1.1 billion yr^{-1} (Table 3). Yearly costs of additional emission reductions for Chicago are estimated to be \$292 million, which are attributed to a 2-$\mu g\ m^{-3}$ increase in yearly averaged $PM_{2.5}$ concentrations in 2050 (Table 2). Necessary SO_2, NO_x, and VOC emission reductions from the Chicago MSA are calculated to be 52, 23, and 14%, respectively. Annual costs of emission reductions for offsetting impacts of climate change on O_3 and $PM_{2.5}$ in Houston and Atlanta are predicted to be \$48 million and \$49 million, respectively (Table 3); this is because yearly averaged $PM_{2.5}$ levels are predicted to decrease in 2050 (Table 2) and reductions in anthropogenic NO_x and VOC emissions are cost-effective for offsetting climate-induced increases in summer O_3 (Table 1). Because emission reductions and associated costs are independent among the five cities, total costs of emission reductions for simultaneously offsetting the impacts of climate change on 4th MDA8hr O_3 and yearly averaged $PM_{2.5}$ for the five cities are the sum of the costs from each of the five cities, but this sum still represents a lower bound of the total nationwide costs for increased controls to offset climate change. The total annual cost for simultaneously offsetting climate impacts on air quality in the five cities is calculated to be up to \$4.1 billion (Table 3); such costs are mainly attributed to the potential climate-induced increases in peak O_3 levels in Los Angeles and New York.

To offset the climate effects on urban air quality, the required ratios of emission reductions in some species for the cities are found to be higher than those from the regions where they are located (e.g., the ratios of reductions in anthropogenic SO_2, NO_x, and VOC emissions from the Chicago and Atlanta MSAs are higher than those of the Great Lakes and Southeast, respectively) (Table 3), and the reductions in regional precursor emissions are not sufficient for offsetting the climate impacts on air quality in the cities. This is because air quality in the cities is more sensitive to climate change than regionally averaged air quality because of higher precursor emission density. Additional controls on anthropogenic NO_x emissions are required for the five cities because NO_x emission reductions are effective for further decreasing O_3 and $PM_{2.5}$ levels in the cities after regional emission reductions have been implemented (Table 4); however, additional controls on SO_2 emissions from only the Chicago MSA are required for further reductions in $PM_{2.5}$ levels in Chicago. Overall, additional annual costs of \$2.6 billion are needed to simultaneously offset the climate impacts on O_3 and $PM_{2.5}$ for the five cities. The costs were estimated by the same least-cost approach (i.e., eq 2), accounting for the implementation of regional emission reductions for the six regions without additional CMAQ-DDM simulations.

A final calculation was to assess costs to overcome the climate penalty on regionally averaged levels and on levels in the five cities; that is, combining the two calculations above, but taking advantage of controls in regional

Table 4. Additional emission reductions (kt) from MSAs as well as total emission reductions and annual costs (1999\$) required for offsetting impacts of climate change on air quality in 2050 for the six regions and five cities.

Region/City	Additional SO_2 Reductions from MSA (kt)	Additional NO_x Reductions from MSA (kt)	Additional VOC Reductions from MSA (kt)	Total SO_2 Reductions (kt)	Total NO_x Reductions (kt)	Total VOC Reductions (kt)	Additional Annual Cost for MSAs (millions of 1999\$)	Total Annual Cost (millions of 1999\$)
Central/Houston	~0	52	~0	~0	202	~0	\$38	\$153
Great Lakes/Chicago	69	72	2	927	503	2	\$89	\$668
Northeast/New York	~0	9	7	228	637	216	\$73	\$5,543
Southeast/Atlanta	~0	48	12	~0	155	12	\$36	\$72
West/Los Angeles	~0	245	196	186	485	196	\$2,370	\$2,656
Mid-Atlantic	–	–	–	216	298	~0	–	\$210
Total (excluding West and Los Angeles)	69	189	60	1371	1735	227	\$248	\$6,646
Total	69	434	256	1557	2220	423	\$2,618	\$9,302

controls impacting levels in the MSAs. The total required reductions in anthropogenic SO_2, NO_x, and VOC emissions from the six regions and five cities are estimated to be 1600, 2200, and 420 kt yr^{-1}, respectively, by 2049–2051 from 2000–2002 levels, and the associated yearly costs are estimated to be $9.3 billion (Table 4). This control cost estimate does not explicitly consider fully overcoming climate-related increases in O_3 and $PM_{2.5}$ levels everywhere in the domain, so there is a possible low bias if the question is what it would cost to overcome the climate penalty everywhere. Opposite biases are introduced from ignoring possible reductions in primary $PM_{2.5}$ emissions, co-benefits of emission controls for multiple precursors, and interstate transport of precursors.

Comparison with the Currently Projected Emission Controls

EPA's Clean Air Interstate Rule (CAIR) requires 28 eastern states and the District of Columbia in the United States to revise their State Implementation Plans (SIPs) to reduce SO_2 and NO_x emissions to improve O_3 and $PM_{2.5}$ levels in the downwind areas.[33] As part of developing CAIR, EPA assessed emission control costs and compared the costs with health and welfare benefits of the rule without considering the effects of future climate change. In December 2008, the U.S. Court of Appeals for the District of Columbia Circuit issued a decision leaving CAIR in effect until a replacement can be put in place (http://www.epa.gov/cair/index.html). The results of this cost analysis can be used here for comparison and help policy-makers include effects of climate change in the future replacement of CAIR. The current assessment of CAIR assumes that a cap-and-trade program will be used to achieve reduction requirements cost-effectively and focused on emissions that have a more regional impact, such as fossil fuel electric generating units (EGUs). Furthermore, because CAIR only covers the eastern United States, the calculated results in this study, excluding the West region and Los Angeles, are compared with the current CAIR estimates. Given that CAIR projects emission control requirements and associated costs until the year 2015, it was assumed that there is no more stringent emission reduction plan thereafter and 2015 estimates are used to compare with the calculated costs for offsetting impacts of climate penalty. CAIR targeted annual emission reductions for SO_2 and NO_x from power plants to be 5400 (57% of power plant SO_2 emissions) and 1300 kt (61% of power plant NO_x emissions), respectively, by 2015 from 2003 levels at an annual incremental cost of $3.6 billion (1999$) in 2015 (on the basis of a 3% discount rate).[33] The additional amount of emission reductions and the associated annual costs of $6.6 billion (Table 4) for offsetting influence of climate change could significantly increase the current estimates for achieving future air quality targets. Using market-based control strategies to offset the impacts of climate penalties on air quality could be more economically efficient; however, using such projections is highly uncertain without considering detailed changes in future social and economic situations and therefore they are not included in this study.

The California South Coast Air Quality Management District (AQMD) also addressed cost-and-benefit analyses for achieving air quality standards in the South Coast Air Basin, including metropolitan Los Angeles and its surrounding counties where current O_3 and $PM_{2.5}$ levels are above standards. SO_2, NO_x, VOC, and primary $PM_{2.5}$ emissions will have to decrease by 56, 29, 11, and 15%, respectively, for $PM_{2.5}$ attainment by 2015 from 2007 levels. Eight-hour average O_3 control strategy builds upon the $PM_{2.5}$ strategy, and NO_x and VOC emissions will have to decrease by 76 and 22%, respectively, by 2024 from 2007 levels without considering impacts of climate penalties on air quality.[34] The annual costs of emission reductions are projected to be at $1.7 billion in 2014 and increase to $4 billion in 2023.[35] The additional reductions in anthropogenic NO_x (~48%) and VOC (~59%) emissions by 2049–2051 from 2000–2002 levels, at a cost of $2.6 billion yr^{-1} (Table 3), for offsetting the climate effects are expected to increase costs required for O_3 and $PM_{2.5}$ attainments over the Los Angeles area in the future. On the other hand, the effects of climate change are not expected to increase currently estimated SO_2 emission reduction requirements in the Los Angeles area because effects of climate change only slightly increase yearly averaged $PM_{2.5}$ levels (Table 2). Although the costs presented in this study and developed by EPA for CAIR and by AQMD for Los Angeles are estimated using different approaches, the comparison of the costs helps policy-makers consider the potential additional concerns of climate change in policy-making.

CONCLUSIONS

Emission reductions and control costs related to offsetting impacts of climate change on O_3 and $PM_{2.5}$ in 2049–2051 are found for the six regions and five cities in the United States. On the basis of the IPCC A1B emission scenario and present emission control technologies, additional least-cost sets of emission reductions for offsetting the impacts of climate change on regionally averaged 4th MDA8hr O_3 and yearly averaged $PM_{2.5}$ are predicted to range from $36 million yr^{-1} (1999$) in the Southeast region to $5.5 billion yr^{-1} in the Northeast region. Total costs of emission reductions for simultaneously offsetting the impacts of climate change on regionally averaged air quality for the six regions are predicted to be approximately $6.7 billion yr^{-1}. Just addressing the five metropolitan areas, costs of approximately $4.1 billion yr^{-1} are projected to offset climate-related air quality impairment. Overall, additional annual costs of $9.3 billion in controls are estimated to offset the impacts of climate change on air quality in 2049–2051 for the six regions and five cities. Additional emission controls and associated costs for offsetting climate impacts everywhere in the domain could be larger than the estimates in this study and may significantly increase the amount of emission reductions and costs required for achieving air quality targets in the future. Current control strategy developments and cost-and-benefit analyses for air quality attainment should include the effects of climate change in the future.

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