Environ. Sci. Technol. **2009,** *43,* 4979–4988

Potential Impact of Climate Change on Air Pollution-Related Human Health Effects

EFTHIMIOS TAGARIS,[†] KUO-JEN LIAO,[†] ANTHONY J. DELUCIA,[‡] LELAND DECK,[§] PRAVEEN AMAR,[||] AND ARMISTEAD G. RUSSELL*[,†]

School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, Georgia, Department of Surgery, James H. Quillen College of Medicine, East Tennessee State University, Johnson City, Tennessee, Stratus Consulting Inc., Washington, DC, Northeast States for Coordinated Air Use Management (NESCAUM), Boston, Massachusetts

Received January 8, 2009. Revised manuscript received April 12, 2009. Accepted April 27, 2009.

The potential health impact of ambient ozone and $PM_{2.5}$ concentrations modulated by climate change over the United States is investigated using combined atmospheric and health modeling. Regional air quality modeling for 2001 and 2050 was conducted using CMAQ Modeling System with meteorology from the GISS Global Climate Model, downscaled regionally using MM5, keeping boundary conditions of air pollutants, emission sources, population, activity levels, and pollution controls constant. BenMap was employed to estimate the air pollution health outcomes at the county, state, and national level for 2050 caused by the effect of meteorology on future ozone and $PM_{2.5}$ concentrations. The changes in calculated annual mean $PM_{2.5}$ concentrations show a relatively modest change with positive and negative responses (increasing $PM_{2.5}$ levels across the northeastern U.S.) although average ozone levels slightly decrease across the northern sections of the U.S., and increase across the southern tier. Results suggest that climate change driven air quality-related health effects will be adversely affected in more than 2/3 of the continental U.S. Changes in health effects induced by $PM_{2.5}$ dominate compared to those caused by ozone. $PM_{2.5}$-induced premature mortality is about 15 times higher than that due to ozone. Nationally the analysis suggests approximately 4000 additional annual premature deaths due to climate change impacts on $PM_{2.5}$ vs 300 due to climate change-induced ozone changes. However, the impacts vary spatially. Increased premature mortality due to elevated ozone concentrations will be offset by lower mortality from reductions in $PM_{2.5}$ in 11 states. Uncertainties related to different emissions projections used to simulate future climate, and the uncertainties forecasting the meteorology, are large although there are potentially important unaddressed uncertainties (e.g., downscaling, speciation, interaction, exposure, and concentration–response function of the human health studies).

Introduction

Mechanisms leading to climate change impacting human health directly or indirectly include heat stress, sea level rise, drowning, water and soil salinization, ecosystem and economic disruption, shortages of food and water supplies, malnutrition, vector-borne disease, food and waterborne diseases, mass population movement, mental health and respiratory disease caused by extreme weather events, and increased air pollutant concentrations (e.g., *1*–*3*). Of interest, here, climate change may alter the exposure to air pollutants by affecting weather and emissions (*4*).

Among the air pollutants examined intensively during the last years for the adverse health effects are ozone and particulate matter (PM). Studies in North America and Europe find that children and patients with chronic lung/heart disease and asthmatics are affected by PM leading to respiratory symptoms and illness, decreased lung function, increased asthma exacerbation, and premature mortality (e.g., *4*–*8*). Young and adult diabetics may be a vulnerable group when exposed to PM (*9*). An important issue when assessing health effects of PM is the time scale used for exposure. Although PM-related health effects are linked to extreme air pollution episodes there is evidence that effects of short-term exposure are a small fraction of the overall effects on human health when compared with long-term exposure (*10*).

Ozone exposure decreases lung function, increases airway reactivity, causes lung inflammation, and decreases exercise capacity (*4*). Bell at al. (*11*, *12*) investigated the acute health effects of ozone exposure over the U.S. for the period 1987–2000. A 10 ppbv increase in ozone level was associated with a 0.52% increase in mortality and 0.64% increase in cardiovascular and respiratory mortality. For a future climate based on the Intergovernmental Panel on Climate Change (IPCC) A2 emissions scenario (*13*), Bell et al. (*14*) estimated that the elevated ozone levels across 50 U.S. cities would lead to a 0.11% to 0.27% increase in daily total premature mortality in the 2050s compared to the 1990s. Based on the same simulations, Knowlton et al. (*15*) estimated a median 4.5% increase in ozone-related acute mortality across the 31 counties in the New York metropolitan region.

Although the potential impact of climate change on human health due to changes in ozone concentrations has been examined to some degree, there are no published studies, to the best of our knowledge, examining the potential impacts on climate change-induced human health effects caused by changes in PM concentrations. This is related to the limited number of studies currently addressing the potential impact of climate change on PM (*16*). The objective of this study is to assess and compare the potential health impacts of ozone and $PM_{2.5}$ under a changed climate over the U.S. and address the related uncertainties. Increases in ground-level ozone concentrations are expected in the future mainly due to higher temperatures and more frequent stagnation events although changes in precipitation will modify $PM_{2.5}$ levels (*17*). Since higher ambient temperatures lead to higher biogenic VOC emissions, future climate-induced emission changes are expected to affect both pollutants' formation (*18*). This work is part of a larger effort to estimate future air pollution health effects quantifying the health costs of the climate penalty. Future impacts (i.e., 2050) are compared with historic periods (i.e., 2001) based on full year of model simulations, keeping emission sources, population, activity levels, and pollution controls constant (i.e., 2001 emission inventory). Although the emission

* Corresponding author tel: 404-894-3079; e-mail: ted.russell@ce.gatech.edu.
[†] Georgia Institute of Technology.
[‡] East Tennessee State University.
[§] Stratus Consulting Inc.
[||] NESCAUM.

10.1021/es803650w CCC: $40.75
Published on Web 05/18/2009

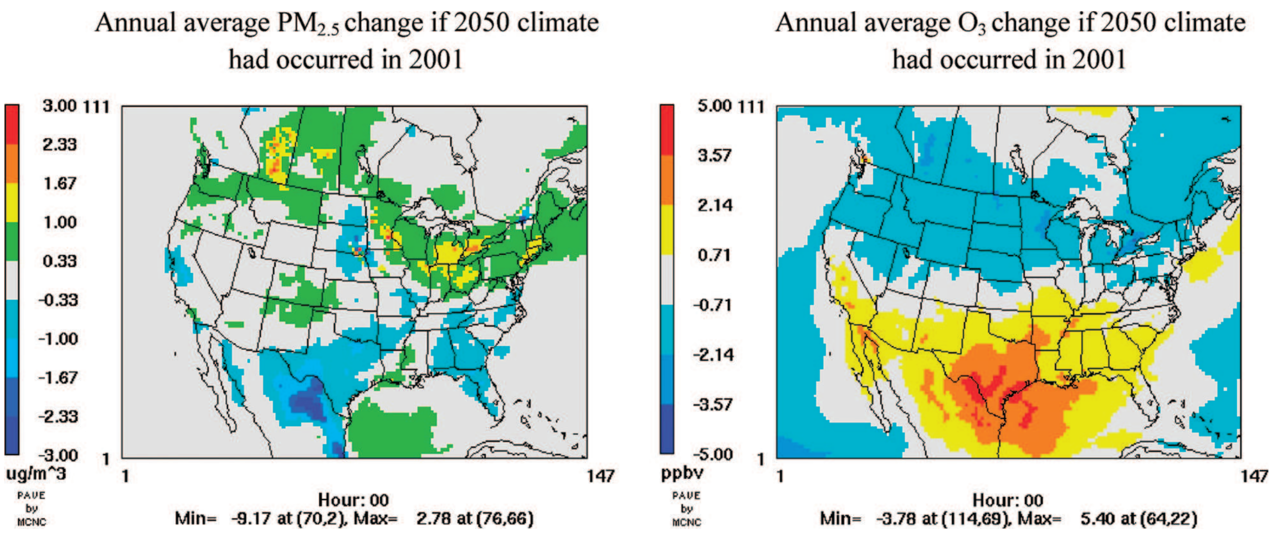

FIGURE 1. Annual $PM_{2.5}$ and ozone concentrations changes in future climate (i.e., 2050) compared to 2001 climate.

inventory is kept the same, emissions are not, since some pollutant emissions (e.g., biogenic and mobile sources) depend on meteorology.

Methods

Air quality modeling for current (i.e., 2001) and future (i.e., 2050) years was conducted using the Community Multiscale Air Quality (CMAQ) Modeling System (*19*). CMAQ is a multipollutant, multiscale air quality model for simulating all atmospheric and land processes that affect transport, transformation, and deposition of atmospheric pollutants on both regional and urban scales. Meteorological fields were derived from the Goddard Institute for Space Studies (GISS) Global Climate Model (GCM) (*20*), which was applied at a horizontal resolution of 4° latitude by 5° longitude (*21*). The simulation covered the period 1950−2055. Observed greenhouse gas concentrations were used during 1950−2000 and the IPCC-A1B emissions scenario (*13*) was used during 2000−2055. The IPCC-A1B emissions scenario is one of the business-as-usual emission scenarios describing a future world with a very rapid economic growth, global population that peaks in midcentury and declines thereafter, and balance across all energy sources and estimates. According to this scenario, global temperature will increase 1.59 degrees in 2050 (*13*). The Penn State/NCAR Mesoscale Model (MM5) (*22*) was used to downscale GISS-GCM outputs to a regional scale with 36-km resolution (*23*). MM5 is a limited-area, nonhydrostatic, terrain-following sigma-coordinate model designed to simulate or predict mesoscale atmospheric circulation. Details of air quality modeling work have been

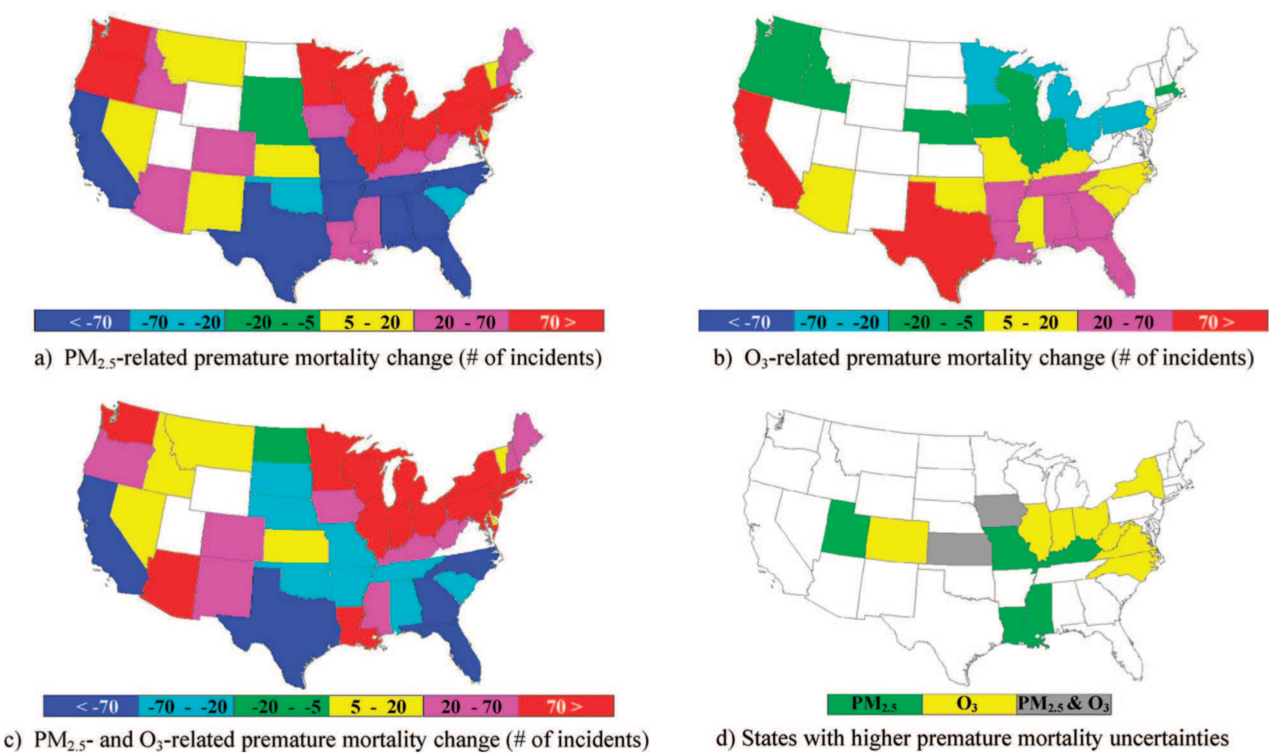

FIGURE 2. State estimated changes of (a) $PM_{2.5}$-related, (b) O_3-related, and (c) both pollutants-related premature mortality in 2050 compared to 2001. (d) States with higher premature mortality uncertainties due to $PM_{2.5}$ and O_3-related effects from uncertainties in meteorology forecasting.

reported elsewhere (*24*). Briefly, that work finds impacts of global climate change alone on regional air quality are small compared to impacts of emission control-related reductions, although increases in pollutant concentrations due to stagnation and other factors are found. Climate change alone modifies mean summer maximum daily 8-h ozone levels ($M8hO_3$) by ± 3% regionally and mean annual $PM_{2.5}$ concentrations by −3% to 6%. The lengthening of stagnation events tends to increase summer ozone concentrations particularly during intense episodes near cities (i.e., New York, Los Angeles, Houston) while climate change has a spatially mixed impact on annual $PM_{2.5}$ levels mainly due to change in precipitation. That work also showed that the selected years are representative of both historic and future periods, using cumulative distribution functions (CDF) and spatial distribution plots for temperature, humidity, and precipitation over three consecutive historic and three consecutive future years. Moreover, simulated and observed annual-average ozone and PM levels tend to be stable for consecutive years. Although ozone is mainly a summer pollutant and the associated health studies for climate change impacts currently focus on summer ozone concentrations, annual analysis is also important since some areas have longer ozone seasons, and there is increasing concern over exposures (human and other) to ozone at lower levels (*25*). For this reason, annual analyses are carried out in this study for both ozone and $PM_{2.5}$.

Health effects analysis was conducted using the U.S. EPA's Environmental Benefits Mapping and Analysis Program (BenMAP) ver. 2.4.8 (http://www.epa.gov/air/benmap). BenMAP includes a rich database of age-specific population, baseline incidence rates, and an extensive library of concentration−response functions for use in analyzing the health effects driven by changes in air quality. The concentration−response functions selected for this analysis are consistent with the functions used by the U.S. EPA in recent regulatory analyses (*25*−*28*). In this work, the population was held constant (i.e., 2000 population) for the future years' analyses. Ozone and $PM_{2.5}$ concentrations are used to estimate the related health effects for 359 days of the year (December holiday week is not modeled due to the population movement and emissions changes).

Ozone-related health effects (and the source of the ozone concentration−response functions used to estimate the change in incidence) estimated in this analysis are:

1 Premature mortality for all ages (*11*);
2 Hospital admissions for respiratory diseases in adults (*29*);
3 Emergency room visits for asthma (all ages) (weighted average of Peel et al. (*30*), Jaffe et al. (*31*), and Wilson et al. (*32*));
4 Days of acute respiratory symptoms for adults ages 18−64 (*33*);
5 School loss days for children ages 5−17 (weighted average of Chen et al. (*34*) and Gilliland et al. (*35*)).

$PM_{2.5}$-related health effects estimated in this analysis (and the source of the PM concentration−response functions used to estimate the change in incidence) are:

1 Premature mortality for both adults ages 30+ (*36*) and postneonatal infants ages 2−12 months (*37*);
2 Onset of new cases of chronic bronchitis in adults, ages 27+ (*38*);
3 Hospital admissions for cardiovascular diseases in adults (ages 18−64 (*34*); ages 65+ weighted average of Mookgavkar et al. (*39*) and Ito et al. (*40*));
4 Days of aggravation of existing asthma in children (i.e., asthma "attacks") ages 6−18 (weighted average of Ostro et al. (*41*) and Vedal et al. (*42*));
5 Cases of acute bronchitis in children ages 8 to 12 (*43*);
6 Days with upper respiratory symptoms in children ages 9 to 11 (*44*);
7 Days with lower respiratory symptoms in children ages 7 to 14 (*45*).

The concentration−response functions we employed in BenMap for $PM_{2.5}$ health impacts consist of those for PM only (no impacts synergistically or antagonistically assigned from various copollutants) and all employ particle mass, without regard to speciation by source category (diesel exhaust, power plant emissions, etc.) and chemical characterization (metals, organics, etc.).

The basic form of the change in premature mortality function (and most of the health functions) associated with a change in air quality is:

$$\left[1 - \frac{1}{\exp(\beta \times \delta)}\right] \times \text{population} \times \text{incidence} \qquad (1)$$

where β is the mortality toxicity factor for ozone [0.00052, (i.e., 1 ppbv change in O_3 concentrations would lead to 0.052% change in the expected number of deaths)] (*11*) or particulate matter [0.0058 (i.e., 1 $\mu g\ m^{-3}$ change in $PM_{2.5}$ concentrations would lead to 0.58% change in the expected number of deaths)] (*36*), δ is the change in air quality, *population* is the age-relevant population in a grid cell and *incidence* is the annual age-relevant mortality rate (as a percent). The results are "population weighted" since the pollutant levels, the population (including age mix), and the age-relevant baseline mortality incidence rate all change by grid cell.

Uncertainties in mortality change are calculated using two different methods of estimating the uncertainty in ozone and PM concentrations. The two methods used to estimate uncertainties in how pollutant levels are impacted by meteorology are (1) from analysis of alternative climate change driven air quality projections (i.e., alternative climates), and (2) from uncertainties in meteorology forecasting. The first method is based on a recent synthesis of multiple groups' modeling of ozone responses to climate change (*46*). As part of a recent combination of results from different global climate and chemical transport models, and regional climate and air quality models, Weaver et al. (*46*) provide simulated future climate and ozone concentrations. These include responses to different greenhouse gas emission scenarios (i.e., IPCC A1B, A2, A1F, B1). The modeling experiments differed in the regional patterns of ozone changes resulting from variations in the patterns of changes in key meteorological drivers, such as temperature and surface insolation. Some regions, such as the Northeast/Mid-Atlantic and Midwest, show greater agreement across results, whereas others, such as the West Coast and the Southeast, show wider disagreements. State-average ozone changes, as well as the range between the maximum and the minimum changes between the various modeling approaches are used here to calculate the related uncertainties.

The second method uses meteorological fields from MIT's Integrated Global System Model (IGSM) simulations (*47*, *48*), in the form of probabilistic distributions, to quantify uncertainties in future meteorology forecasting and their associated effects on regional air quality, described in details elsewhere (*49*). Briefly, in that work, air temperature and absolute humidity simulated from MIT IGSM's outputs are remapped onto MM5 meteorological fields driven by GISS-GCM. Temperature and absolute humidity are chosen for perturbation as they are strongly correlated with regional ozone and secondary $PM_{2.5}$ levels. Intermediate meteorological outputs after remapping air temperature and absolute humidity are used for rerunning MM5 to get conservative mesoscale meteorological fields. Three percentiles of MIT-IGSM probabilistic distributions for both meteorological variables have been applied: 0.5th, 50th, and 99.5th percentiles for low, base, and high extreme scenarios, respec-

TABLE 1. National Total and State Specific Estimated Changes of $PM_{2.5}$-Related Health Effects in 2050 Compared to 2001 (Mean Estimates and 5th and 95th Percentiles of Confidence Levels)

	premature mortality (no. of incidents)			chronic bronchitis (no. of incidents)			hospital admissions, cardiovascular (no. of incidents)			asthma "attacks" (no. of days)			acute bronchitis (no. of incidents)			upper respiratory symptoms (no. of days)			lower respiratory symptoms (no. of days)		
	percentiles			percentiles			percentiles			percentiles			percentiles			percentiles			percentiles		
	fifth	50th (mean)	95th	fifth	50th (mean)	95th	fifth	50th (mean)	95th	fifth	50th (mean)	95th	fifth	50th (mean)	95th	fifth	50th (mean)	95th	fifth	50th (mean)	95th
national total	**1377**	**3711**	**6066**	**386**	**2438**	**4552**	**1103**	**2030**	**3148**	**22399**	**218335**	**504978**	**−401**	**6357**	**13500**	**15695**	**60463**	**114879**	**85868**	**344528**	**756652**
state																					
AL	−31	−84	−136	−7	−46	−84	−21	−33	−44	−461	−2998	−4256	8	−120	−245	−355	−1108	−1721	−95	1481	4929
AZ	22	60	98	7	44	81	14	24	34	458	3706	7221	−8	126	261	341	1182	2052	851	2191	3934
AR	−27	−72	−118	−6	−37	−68	−16	−25	−34	−337	−2256	−3377	6	−98	−200	−258	−815	−1285	−138	744	2774
CA	−70	−186	−302	−21	−133	−243	−32	−49	−60	−1024	−5396	−4256	23	−341	−683	−830	−2385	−3319	1137	9982	27419
CO	22	58	95	8	51	94	14	24	34	500	3992	7663	−9	135	280	367	1264	2181	858	2084	3566
CT	86	232	379	23	148	275	71	124	180	1285	10631	21222	−24	376	790	953	3343	5867	2638	7434	14355
DE	3	8	13	1	5	10	2	4	7	48	507	1243	−1	15	30	32	131	260	209	831	1912
DC	1	2	3	0	2	3	1	1	2	13	129	313	0	4	8	9	35	69	53	211	485
FL	−148	−396	−644	−34	−215	−394	−109	−181	−248	−1770	−12821	−21728	32	−485	−993	−1341	−4398	−7216	−1713	−883	2988
GA	−61	−163	−266	−18	−113	−207	−44	−70	−90	−1225	−7557	−9619	20	−310	−637	−960	−2936	−4441	177	6166	18832
ID	9	23	37	3	16	30	5	8	12	179	1458	2857	−3	51	105	130	451	784	331	869	1585
IL	147	396	647	44	282	524	114	205	307	2992	26543	56805	−52	820	1729	2181	7947	14439	8013	26550	56210
IN	102	275	449	27	171	317	70	125	187	1732	15211	32248	−31	485	1016	1239	4494	8134	4395	14281	29838
IA	12	32	52	3	20	37	14	28	49	263	3067	7396	−3	50	106	165	656	1192	4064	36546	53535
KS	2	6	10	1	5	10	3	6	11	78	947	2531	−1	17	35	51	228	483	463	1928	4425
KY	19	52	85	5	33	61	13	23	37	266	2653	6261	−5	83	172	183	715	1377	994	3771	8432
LA	21	57	93	6	35	64	14	27	42	363	3647	8647	−7	103	216	244	960	1858	1360	5192	11639
ME	17	46	76	4	27	50	13	23	33	225	1834	3603	−4	64	133	164	571	996	423	1122	2062
MD	34	90	147	11	66	123	26	49	78	554	5871	14458	−11	172	357	382	1556	3088	2491	9950	22971
MA	122	328	536	33	212	393	99	172	248	1751	14392	28531	−33	509	1067	1286	4495	7862	3451	9494	17979
MI	232	624	1018	65	411	762	162	282	409	3958	32786	65565	−73	1139	2398	2907	10203	17917	8096	22925	44351
MN	81	218	357	26	168	313	68	121	180	1747	15100	31388	−29	459	969	1253	4480	7957	4728	20556	60404
MS	12	33	53	3	18	34	7	13	20	169	1718	4111	−4	54	114	112	447	872	656	2519	5628
MO	−29	−78	−127	−7	−45	−82	−16	−25	−30	−378	−2161	−2275	8	−118	−241	−301	−890	−1291	215	2612	7399
MT	6	16	26	2	10	18	3	6	8	97	776	1489	−2	26	54	71	243	420	165	417	807
NE	−7	−19	−31	−2	−11	−20	−3	−3	−2	−69	−235	140	2	−30	−61	−58	−164	−238	1268	5891	10916
NV	4	12	20	1	9	16	2	4	6	85	702	1405	−2	23	48	63	222	390	177	497	943
NH	22	60	98	7	41	77	18	32	46	376	3068	6042	−7	109	228	279	972	1696	728	1964	3677
NJ	185	497	811	52	330	611	152	271	404	2777	24482	52115	−53	826	1731	2043	7419	13430	7373	24540	52980
NM	6	16	26	2	12	23	3	6	8	111	934	1895	−2	33	68	82	289	511	240	700	1361
NY	314	846	1379	88	555	1029	260	459	673	4851	41315	85026	−91	1420	2976	3578	12747	22693	11243	34645	71411
NC	−35	−95	−154	−10	−61	−111	−29	−44	−53	−667	−3684	−3460	10	−153	−314	−532	−1559	−2228	538	5502	15405
ND	−1	−4	−6	0	−2	−3	0	0	0	−6	20	191	0	−4	−9	−6	−10	2	57	311	824
OH	211	566	923	54	339	629	139	244	358	3057	25896	52987	−57	890	1864	2215	7874	13994	6790	20357	40561
OK	−16	−43	−70	−3	−22	−40	−9	−14	−17	−189	−1076	−1109	4	−57	−118	−146	−433	−631	118	1390	3994
OR	29	79	128	9	54	100	16	27	39	490	3951	7675	−9	140	292	358	1240	2150	882	2255	4037
PA	173	464	756	41	257	476	133	237	355	2174	19440	41917	−41	629	1312	1551	5685	10377	5886	19847	42510
RI	16	43	70	4	26	49	13	22	32	232	1901	3749	−4	66	139	168	586	1023	441	1191	2219
SC	−13	−35	−56	−3	−21	−38	−11	−17	−19	−280	−1372	−735	4	−56	−115	−226	−635	−856	403	3176	8576
SD	−7	−18	−30	−2	−12	−21	−2	−1	17	−78	−295	−77	2	−32	−65	−68	−196	−279	2100	5878	14305
TN	−32	−85	−138	−8	−49	−91	−22	−35	−45	−476	−3004	−4023	8	−123	−253	−370	−1141	−1747	−11	1963	6144
TX	−200	−536	−871	−66	−412	−754	−135	−223	−301	−4025	−28332	−46024	82	−1241	−2528	−3070	−9934	−16058	−3058	2136	16939

TABLE 1. Continued

	premature mortality (no. of incidents)			chronic bronchitis (no. of incidents)			hospital admissions, cardiovascular (no. of incidents)			asthma "attacks" (no. of days)			acute bronchitis (no. of incidents)			upper respiratory symptoms (no. of days)			lower respiratory symptoms (no. of days)		
	percentiles			percentiles			percentiles			percentiles			percentiles			percentiles			percentiles		
	fifth	50th (mean)	95th	fifth	50th (mean)	95th	fifth	50th (mean)	95th	fifth	50th (mean)	95th	fifth	50th (mean)	95th	fifth	50t (mean)	95th	fifth	50th (mean)	95th
national total	**1377**	**3711**	**6066**	**386**	**2438**	**4552**	**1103**	**2030**	**3148**	**22399**	**218335**	**504978**	**−401**	**6357**	**13500**	**15695**	**60463**	**114879**	**85868**	**344528**	**756652**
state																					
UT	0	1	2	0	1	2	0	1	1	23	256	647	0	4	8	15	61	125	109	439	995
VT	3	7	11	1	3	6	3	5	8	35	381	927	0	7	15	23	100	207	152	629	1902
VA	−1	−2	−3	2	12	22	1	5	15	30	1441	5405	−2	28	60	−1	194	670	1303	6275	15259
WA	52	139	226	16	101	186	29	49	70	922	7418	14360	−17	264	549	677	2341	4053	1641	4132	7306
WV	16	43	70	4	22	41	10	17	26	161	1440	3101	−3	50	104	113	415	757	426	1416	2970
WI	73	196	320	20	129	239	59	105	154	1364	11759	24488	−22	344	719	969	3476	6225	3207	10332	22796
WY	1	2	4	0	2	3	1	1	1	18	150	295	0	4	9	13	45	78	33	89	163

tively. That work showed that impacts of the extreme scenarios on concentrations of summer maximum daily 8-h ozone ($M8hO_3$) are predicted to be up to 10 ppbv in urban areas of the Northeast, Midwest, and Texas, though average differences in ozone concentrations are about 1−2 ppbv on a regional basis. Differences between the extreme and base scenarios in annual $PM_{2.5}$ levels are very location-dependent and predicted to range between −1.0 and +1.5 $\mu g\,m^{-3}$. Future $PM_{2.5}$ levels are less sensitive to the extreme scenarios than summertime peak ozone since precipitation scavenging is only slightly affected by the extreme scenarios examined. State-average ozone and $PM_{2.5}$ changes are used here to calculate the related uncertainties.

Assuming a linear response for small changes in pollutant concentrations, the mortality change, DM_2, caused by the related change in pollutant concentration, DC_2, is calculated as

$$DM_2(x, t) = \frac{DC_2(x, t)}{DC_1(x, t)} DM_1(x, t) \qquad (2)$$

where $DM_1(x,t)$ is the mortality change at location x and time t caused by the related change in pollutant concentrations $DC_1(x,t)$. Setting $DC_2(x,t)$ as the range (uncertainty) in state-average pollutant concentration changes and for $DC_1(x,t)$ the state-average pollutant concentration changes during the year for which the change in mortality $DM_1(x,t)$ has been estimated, provides an estimate of uncertainty in the calculated mortality change $DM_2(x,t)$. This mortality change is "population-weighted" since the original mortality change ($DM_1(x,t)$) is "population-weighted" and the ratio in pollutant concentrations (i.e., $DC_2(x,t)/DC_1(x,t)$) is the average state values.

Results and Discussion

Baseline Air Quality. The changes in calculated annual mean $PM_{2.5}$ concentrations between 2001 and 2050 (Figure 1) show a relatively modest change with positive and negative responses (increasing $PM_{2.5}$ levels in the Great Lakes area, and overall across the northeastern U.S.). Changes in annual mean ozone concentrations between 2001 and the future year find average ozone levels slightly decreasing across the northern sections of the U.S., and increasing across the southern tier (Figure 1). The geographic pattern of changes in annual mean ozone changes is significantly different from the pattern observed for $PM_{2.5}$. One reason is that the seasonal pattern of ozone (peaking in the summer, with relatively low concentrations in the winter months), interacting with seasonal patterns of climate-induced meteorological changes, may be a significant causal factor in the pattern of annual mean ozone changes, but not of PM, since generally this category of pollutants exhibits somewhat less seasonal variation. The weaker correlation of PM concentrations with meteorological variables compared to ozone is described in detail elsewhere (*17*).

Health Impacts. BenMap calculations based on the calculated changes in $PM_{2.5}$ and ozone show some locations with a decrease in air pollution-related health effects while other locations show an exacerbation in health effects (Tables 1 and 2). Since changes in the estimated air pollution-related health effects depend on the changes in both air quality and the size of the population exposed to those changes, air quality changes in the densely populated sections of the country have a greater effect than air quality changes in less densely populated areas. Modeling results suggest that worsened ozone and $PM_{2.5}$ levels will coincide spatially with many of the most densely populated areas of the country, while many of the areas estimated to have improved air quality are in the least densely populated areas of the country.

Impacts of climate change on $PM_{2.5}$-related human health effects are estimated to have an increasing trend with time

TABLE 2. National Total and State Specific Estimated Changes of Ozone-Related Health Effects in 2050 Compared to 2001 (Mean Estimates and 5th and 95th Percentiles of Confidence Levels)

	premature mortality (no. of incidents)			hospital admissions, respiratory (no. of incidents)			acute respiratory symptoms (no. of days)			emergency room visits, respiratory (no. of incidents)			school loss days (no. of days)		
	percentiles			percentiles			percentiles			percentiles			percentiles		
	fifth	50th (mean)	95th	fifth	50th (mean)	95th	fifth	50th (mean)	95th	fifth	50th (mean)	95th	fifth	50th (mean)	95th
national total	**111**	**279**	**462**	**2199**	**9699**	**22223**	**2038502**	**4583140**	**7587702**	**−750**	**1618**	**5702**	**485182**	**1427113**	**2524983**
state															
AL	10	23	36	133	402	742	36215	79049	127605	−3	39	109	8471	26905	47267
AZ	8	19	30	100	304	560	82828	173376	269438	−3	40	106	21353	61141	103404
AR	9	21	34	122	365	667	29202	62916	100406	−3	34	93	7080	22766	40065
CA	35	82	131	426	1307	2436	592803	1237660	1918702	−24	235	630	162160	459635	775320
CO	−2	−4	−6	−15	−23	−10	8119	18584	31199	−4	2	11	1749	4012	7833
CT	−2	−3	−5	−7	42	170	25187	57411	96178	−2	23	70	5585	15515	27268
DE	0	−1	−1	−1	9	34	5081	11432	18933	0	5	15	1154	3303	5843
DC	0	0	0	0	3	8	1324	3105	5315	0	1	3	243	694	1235
FL	12	30	49	255	1006	2191	17964	59645	125103	−23	9	84	1664	12927	32357
GA	14	34	53	185	569	1066	24748	65771	122703	−3	42	142	4780	21364	42674
ID	−2	−5	−8	−22	−55	−83	−5156	−10146	−14818	−12	−5	0	−1505	−5277	−8758
IL	−8	−17	−26	−47	139	653	33070	99027	197731	−50	24	211	4773	11162	26154
IN	−2	−5	−8	−4	116	395	6663	26628	59994	−11	10	86	5	1163	6444
IA	−3	−8	−12	−42	−55	−3	2731	9552	20463	−7	1	24	206	−186	934
KS	0	1	2	14	80	200	16319	37083	61946	−3	24	77	3835	10840	19346
KY	3	8	13	57	219	470	28543	64696	107801	−2	30	90	6053	18457	33208
LA	13	32	51	180	546	1010	63950	140070	226844	−5	68	191	16020	49686	86572
ME	−2	−4	−6	−18	−37	−43	−3523	−6118	−7663	−11	−5	1	−965	−2910	−4501
MD	−1	−3	−4	4	109	340	53097	121731	204697	−4	46	141	11465	32605	57625
MA	−3	−6	−8	−11	74	291	42682	96928	161860	−3	39	117	8574	23885	42322
MI	−18	−43	−67	−218	−403	−384	−32955	−48902	−46493	−162	−84	12	−10765	−33449	−50293
MN	−11	−26	−40	−154	−333	−426	−15891	−26051	−29870	−87	−44	5	−4889	−17755	−27909
MS	6	14	22	78	240	448	22587	49351	79740	−2	25	71	5738	18421	32566
MO	8	19	30	130	439	875	54564	119988	194986	−8	105	302	12951	38953	68193
MT	−2	−4	−7	−19	−47	−70	−5212	−10338	−15227	−9	−4	0	−1379	−4436	−7315
NE	−3	−6	−10	−37	−71	−76	205	2353	6480	−9	−2	11	−218	−1468	−1910
NV	0	1	1	5	22	48	10859	23020	36190	−1	2	6	2506	6746	11712
NH	−1	−2	−4	−11	−16	−6	776	2970	6594	−4	0	6	46	−89	280
NJ	6	16	26	133	552	1233	161234	354172	575121	−14	175	482	35687	104712	181217
NM	2	4	7	24	74	138	15159	31932	49912	−1	10	26	4179	12284	21133
NY	−2	−3	−4	38	345	968	143855	321464	529754	−31	136	411	30997	88568	154962
NC	4	9	16	73	297	657	21693	56746	104818	−2	19	77	3735	13490	27400
ND	−2	−4	−6	−22	−52	−74	−2706	−5218	−7454	−14	−6	1	−769	−2595	−4215
OH	−12	−28	−43	−113	−54	309	5958	34406	85649	−36	−3	105	−1228	−5118	−1816
OK	7	16	26	99	313	595	29951	65797	106818	−2	30	88	7238	22165	39097
OR	−5	−13	−20	−54	−126	−182	−4238	−6626	−7007	−16	−7	1	−1313	−5552	−8814
PA	−9	−20	−30	−64	70	499	54175	131454	230790	−24	47	179	11334	31907	59262
RI	0	−1	−1	0	20	66	7042	15852	26285	−1	7	20	1560	4390	7751
SC	5	13	21	79	255	496	18684	43208	73171	−2	21	64	4057	13887	25802
SD	−1	−3	−5	−20	−43	−53	−2808	−5148	−6929	−12	−6	1	−870	−2778	−4374
TN	9	21	34	124	402	781	36263	81232	134027	−3	39	113	7971	26160	47346
TX	68	161	256	960	2774	4943	438632	933946	1474936	−43	517	1411	116049	354378	607299

TABLE 2. Continued

	premature mortality (no. of incidents)			hospital admissions, respiratory (no. of incidents)			acute respiratory symptoms (no. of days)			emergency room visits, respiratory (no. of incidents)			school loss days (no. of days)		
	percentiles			percentiles			percentiles			percentiles			percentiles		
	fifth	50th (mean)	95th	fifth	50th (mean)	95th	fifth	50th (mean)	95th	fifth	50th (mean)	95th	fifth	50th (mean)	95th
national total	**111**	**279**	**462**	**2199**	**9699**	**22223**	**2038502**	**4583140**	**7587702**	**−750**	**1618**	**5702**	**485182**	**1427113**	**2524983**
state															
UT	−1	−2	−3	−9	−18	−17	945	2465	4539	−6	−2	1	181	−194	346
VT	−1	−2	−3	−8	−15	−16	−1576	−2717	−3370	−5	−3	0	−441	−1341	−2029
VA	0	1	2	26	177	466	29216	73760	133091	−5	21	85	4911	15197	29861
WA	−5	−11	−17	−43	−79	−77	3298	10848	22649	−15	−4	8	−98	−1945	−1831
WV	−1	−2	−3	−5	22	94	1134	4856	11176	−3	−1	6	−8	118	1270
WI	−8	−18	−28	−95	−149	−81	−12338	−16490	−11949	−56	−30	9	−4183	−13585	−19938
WY	−1	−2	−3	−7	−17	−25	−1851	−3590	−5162	−4	−2	0	−497	−1645	−2682

(Table 1). The situation is estimated to be worse in the future (i.e., more incidents) in more than $^2/_3$ of the states: New York, along with the states in the Great Lakes and the northeastern U.S. will be affected more. Conversely, Texas and the southeastern states will have fewer incidents. About 4000 more $PM_{2.5}$-related premature deaths are projected nationally for 2050 compared to 2001. Four states will be almost unaffected, 17 states will be moderately negatively affected, four states will be moderately positively affected, while 14 states will be very negatively affected and nine states will be very positively affected (Table 1, Figure 2). About 2000 more chronic bronchitis and hospital admissions for cardiovascular diseases and 6000 more acute bronchitis incidents are projected nationally in 2050. The situation will be worse for upper respiratory symptoms (~60,000), asthma attacks (~200,000) and lower respiratory symptoms (~350,000) days.

Ozone-related premature mortality and hospital admissions for respiratory symptoms are estimated to increase in the future (Table 2). About 300 more ozone-related premature deaths are projected nationally and 10,000 more hospital admissions for respiratory symptoms for 2050 compared to 2001. The days of acute respiratory symptoms and school-days loss are projected to increase. About 1500 more incidents in emergency room visits for asthma are expected in the near future. Fewer adverse health outcomes are estimated in some states (e.g., Minnesota and Michigan) and more in others (e.g., Texas and California). Climate change-related increased ozone health effects are less pronounced in the Great Lakes area and more pronounced for the southern states. Significantly more premature deaths are estimated to be concentrated in 16 states while significantly fewer in 13 (Table 2, Figure 2). The results presented here for ozone-related human health effects are different from those presented by Bell et al. (*14*) since the two studies are based on different emissions scenarios for climate change, and Bell et al. concentrated on 50 U.S. cities. The emissions scenario followed here (i.e., IPCC-A1B) estimates ozone reduction in the northeastern and northcentral regions of the U.S. resulting in less incidents in 2050 while the emissions scenario followed by Bell et al. (i.e., IPCC-A2) estimates increases in ozone concentrations, particularly in the Great Lakes area.

Changes in health effects due to changes in $PM_{2.5}$ dominate those due to ozone. Estimated climate-induced changes in air pollution-related premature mortality, nationally, caused by $PM_{2.5}$ increases is about 15 times higher than by ozone increases. The increase in mortality due to ozone concentrations will be offset by a decrease in $PM_{2.5}$ mortality in 11 states (Table 1, Table 2, Figure 2). At the same time, the decreasing mortality from ozone reductions (i.e., more than five incidents) does not dominate impacts from higher $PM_{2.5}$ in 12 states. In six states both pollutants result in increased premature mortality.

Results of both the climate change and the air quality modeling have associated uncertainties (*46, 49*). Quantification of uncertainties in 2050 mortality is conducted here. In the first approach, the range in state-average summertime ozone changes as predicted by different modeling systems and emissions projections is used to calculate uncertainties (Table 3). The big differences in ozone concentrations across the different simulations as a result from the variation in the simulated patterns of mean changes in key meteorological drivers give a big range in ozone mortality. FL, OH, and TX have the highest mortality change range while RI, NM, DE, WY, ND, NV, and KS have the smallest calculated range. There is good agreement in the related ozone mortality change for NY based on the IPCC-A2 emissions scenario between our analysis (+60 premature mortality change due to ozone exposure) and the results presented by Knowlton et al. (*15*) (+54 mortality change).

TABLE 3. State-Specific Estimated Uncertainties for Ozone and $PM_{2.5}$ Climate-Induced Changes in 2050 Compared to 2001

	different models and emissions scenarios (2050s−2000s)				meteorology (2050 uncertainty)							
	summer time ozone				summer time ozone				annual $PM_{2.5}$			
	ozone change (ppbv)		mortality change[a] (no. of incidents)		ozone change (ppbv)		mortality change[a] (no. of incidents)		$PM_{2.5}$change (μg m^{-3})		mortality change[a] (no. of incidents)	
	min	max	min	max	min	max	min	max	min	max	min	max
AL	−5.5	7.0	−84	107	−1.0	2.5	−15	38	−0.5	0.7	−84	117
AZ	−5.0	3.0	−63	38	−1.0	2.5	−13	32	−0.3	0.2	−90	60
AR	−4.0	5.0	−42	53	−1.5	3.0	−16	32	−0.1	0.2	−14	29
CA	−3.0	3.0	−123	123	−1.0	2.0	−41	82	−0.2	0.2	−186	168
CO	−1.5	2.5	−50	30	−1.0	2.0	−40	20	−0.1	0.2	−19	39
CT	−0.5	6.5	−39	3	−1.0	2.0	−12	6	−0.2	0.2	−36	27
DE	−3.0	3.5	−7	6	−1.0	2.0	−4	2	−0.3	0.1	−4	12
DC	2.5	9.5	0	0	−1.0	3.0	0	0	−0.4	0.2	−3	2
FL	−5.5	7.0	−330	420	−1.0	1.0	−60	60	−0.4	0.5	−226	283
GA	−4.0	4.5	−136	153	−1.0	2.5	−34	85	−0.7	0.7	−229	229
ID	−3.0	5.5	−30	55	−1.0	0.2	−10	2	−0.1	0.2	−7	23
IL	−2.0	4.5	−153	68	−1.5	3.0	−102	51	−0.6	0.3	−793	330
IN	−2.5	4.5	−25	45	−1.5	3.0	−15	30	−0.8	0.2	−295	79
IA	−3.0	5.5	−48	88	−1.0	3.0	−16	48	−0.7	0.0	−225	3
KS	−4.0	5.5	−8	11	−1.5	3.0	−3	6	−0.5	0.2	−15	6
KY	−1.0	5.0	−8	40	−1.5	3.0	−12	24	−0.4	0.1	−209	26
LA	−5.5	7.0	−88	112	−1.5	3.0	−24	48	−0.4	0.8	−76	153
ME	−2.5	3.5	−10	14	−1.0	0.5	−4	2	−0.3	0.2	−23	19
MD	1.5	8.0	−34	−6	−1.0	2.5	−11	4	−0.4	0.0	−181	5
MA	−1.5	7.0	−84	18	−1.0	2.0	−24	12	−0.4	0.1	−96	19
MI	−2.0	2.5	−57	72	−1.0	2.0	−29	57	−0.7	0.4	−437	218
MN	−2.0	3.0	−35	52	−1.0	2.0	−17	35	−0.6	0.4	−164	96
MS	−5.0	5.5	−70	77	−1.0	3.0	−13	42	−0.5	0.7	−49	77
MO	−2.0	4.5	−21	48	−1.5	3.0	−16	32	−0.5	0.3	−195	97
MT	−3.0	5.5	−10	18	−1.0	2.0	−3	7	−0.3	0.1	−10	4
NE	−2.0	4.5	−12	27	−1.5	3.0	−9	18	−0.5	0.1	−32	6
NV	−2.5	7.0	−14	5	−1.0	1.0	−2	2	−0.1	0.2	−7	24
NH	−1.5	5.0	−6	20	−1.0	1.0	−4	4	−0.4	0.2	−34	13
NJ	2.0	6.0	21	64	−1.0	2.0	−11	21	−0.3	0.1	−213	71
NM	−3.0	1.5	−7	4	−1.0	2.5	−2	6	−0.1	0.2	−5	16
NY	−1.5	6.0	−15	60	−1.0	2.5	−10	25	−0.5	0.2	−604	181
NC	−0.5	4.5	−15	135	−1.0	2.5	−30	75	−0.3	0.3	−71	71
ND	−2.0	3.5	−6	11	−1.0	2.0	−3	6	−0.3	0.1	−5	2
OH	−2.0	4.5	−187	420	−1.0	3.0	−93	280	−0.8	0.3	−453	142
OK	−5.0	5.0	−53	53	−1.3	3.5	−14	37	−0.2	0.2	−22	22
OR	−2.5	6.5	−46	121	−1.0	0.2	−19	4	−0.1	0.2	−16	53
PA	0.5	5.5	20	220	−1.0	1.5	−40	60	−0.4	0.0	−371	9
RI	−0.5	5.5	−6	1	−0.9	1.5	−2	1	−0.4	0.2	−17	9
SC	−2.0	4.5	−33	73	−1.0	2.5	−16	41	−0.5	0.5	−58	58
SD	−2.5	4.0	−8	12	−1.0	2.5	−3	8	−0.6	0.1	−27	5
TN	−2.0	4.0	−28	56	−1.4	3.0	−20	42	−0.4	0.4	−85	74
TX	−5.0	4.0	−230	184	−1.5	3.5	−69	161	−0.1	0.3	−40	201
UT	−3.0	5.0	−20	33	−1.0	1.0	−7	7	−0.2	0.2	−2	2
VT	−1.5	5.5	−5	18	−1.0	0.5	−3	2	−0.4	0.2	−5	3
VA	1.0	5.5	10	55	−1.0	3.0	−10	30	−0.3	0.1	−3	1
WA	−2.5	7.0	−34	96	−1.0	0.5	−14	7	−0.2	0.2	−42	56
WV	−0.5	5.0	−3	33	−1.0	3.0	−7	20	−0.3	0.1	−54	21
WI	−2.5	3.5	−56	79	−1.0	2.0	−23	45	−0.8	0.3	−224	70
WY	−1.5	4.5	−4	11	−1.0	1.0	−3	3	−0.1	0.2	−2	5
national total			-2292	3436			−948	1662			−6058	3236

[a] Mortality change is the change in premature deaths attributed to the associated pollutant.

Using the second approach, state-average ozone and $PM_{2.5}$ concentration changes between the two extreme cases and the base-case scenario developed for air quality simulations are used to calculate uncertainties in pollutant levels from uncertainties in meteorology forecasting (Table 3). Small changes in various processes that control climate lead to relatively large changes in meteorology. As a result, ozone and PM estimates are somewhat more uncertain locally due to the dependency of air quality on meteorological variables (e.g., temperature, regional stagnation, wind speed, mixing depth, humidity, cloud cover, precipitation) that change under the extreme cases examined here. Uncertainties in meteorology appear to be more important for PM-related health effects than for ozone, since 1 μg m^{-3} change in $PM_{2.5}$ concentration alters the related mortality about 10 times more than 1 ppbv change in ozone concentration (*11, 36*), while the average states' uncertainty range is 3.3 ppbv and 0.6 μg m^{-3} for ozone and $PM_{2.5}$, respectively. As a result, uncertainties forecasting the meteorology lead to calculated $PM_{2.5}$-related premature mortality in IA, KY, LA, UT, MS, MO, and KS being most uncertain while ozone-related premature mortality uncertainties are large in 10 states (Figure 2).

Future impacts of climate change, as reported here, would be underreported since obviously not all adverse outcomes of ozone and PM exposure on human health have been included in the assessment. As mentioned in the methods, no synergistic or antagonistic impacts of copollutants were assessed and it is therefore possible that the effects we predict would be lower or higher, respectively, when exposures to two or more pollutants are simultaneously experienced. Additionally, we base our estimates of health impacts, locally and nationally, on population, mortality rates, and disease incidence rates obtained from the U.S. Census and the U.S. Centers for Disease Control and Prevention data for 2000. The combination of anticipated changes in the population (increasing by 2050) and age-specific mortality rates (expected to continue to decrease) would affect future health estimates for 2050; the net effect would likely increase the estimated health effects.

This work suggests that climate change impacts on conventional air pollutants and human health could be substantial but the results are subject to significant uncertainties. Impacts of climate change on air pollution-related human health are estimated to have an increasing trend with time. As is often the case in air pollution health analyses, the $PM_{2.5}$-related health effects dominate the ozone-related health effects but the geographic pattern of changes in ozone concentrations is significantly different than the patterns observed for $PM_{2.5}$. Although in this analysis a "what if" approach is used to compare the hypothetical situation of what would happen if the predicted future climate conditions occurred in 2001 (e.g., holding the anthropogenic emission inventory and population constant) the information provided here will enhance the ability of air quality managers to consider global change in their decisions, integrating the potential impact of climate change on both ozone- and $PM_{2.5}$-related human health and the related uncertainties.

Acknowledgments

This work was supported by the National Center for Energy Policy (NCEP) and U.S. EPA STAR grants: RD83096001, RD82897602, RD83183801, and RD83107601.

Literature Cited

(1) Patz, J. A.; McGeehin, M. A.; Bernard, S. M.; Ebi, K. L.; Epstein, P. R.; Grambsch, A.; Gubler, D. J.; Reiter, P.; Romieu, I.; Rose, J. B.; Samet, J. M.; Trtanj, J. The Potential Health Impacts of Climate Change Variability and Change for the United States: Executive Summary of the Report of the Health Sector of the U.S. National Assessment. *Environ. Health Perspect.* **2000**, *108* (4), 367–376.

(2) Frumkin, H.; Hess, J.; Luber, G.; Malilay, J.; McGeehin, M. Climate Change: The Public Health Response. *Am. J Public Health* **2008**, *98* (3), 435–445.

(3) Tamerius, J. D.; Wise, E. K.; Uejio, C. K.; McCoy, A. L.; Comrie, A. C. Climate and Human Health: Synthesizing Environmental Complexity and Uncertainty. *Stoch. Environ. Res. Risk Assess.* **2007**, *21*, 601–613.

(4) Bernard, S. M.; Samet, J. M.; Grambsch, A.; Ebi, K. L.; Romieu, I. The Potential Impacts of Climate Variability and Change on Air Pollution-Related Health Effects in the United States. *Environ. Health Perspect.* **2001**, *19* (2), 199–209.

(5) Peng, R. D.; Dominici, F.; Pastor-Barriuso, R.; Zeger, S. L.; Samet, J. M. Seasonal Analyses of Air Pollution and Mortality in 100 US Cities. *Am. J. Epidemiol.* **2005**, *161*, 585–594.

(6) Ballester, F.; Medina, S.; Boldo, E.; Goodman, P.; Neuberger, M.; Iniguez, C.; Kunzli, N. Reducing Ambient Levels of Fine Particulates Could Substantially Improve Health: A Mortality Impact Assessment for 26 European Cities. *J. Epidemiol. Commun. Health* **2008**, *26* (2), 98–105.

(7) Araujo, J. A.; Barajas, B.; Kleinman, M.; Wang, X. P.; Bennett, B. J.; Gong, K. W.; Navad, M.; Harkema, J.; Sioutas, C.; Lusis, A. J.; Nel, A. E. Ambient Particulate Pollutants in the Ultrafine Range Promote Early Atherosclerosis and Systemic Oxidative Stress. *Circ. Res.* , *102* (5), 589–596.

(8) Bell, M. L.; Dominici, F.; Ebisu, K.; Zeger, S. L.; Samet, J. M. Spatial and Temporal Variation in $PM_{2.5}$ Chemical Composition in the United States for Health Effects Studies. *Environ. Health Perspect.* **2007**, *115* (7), 989–995.

(9) O'Neill, M. S.; Veves, A.; Sarnat, J. A.; Gold, D. R.; Horton, E. S.; Schwartz, J. Air Pollution and Infammation in Type 2 Diabetes: A Mechanism for Susceptibility. *Occup. Environ. Med.* **2007**, *64*, 373–379.

(10) Pope, C. A. Mortality Effects of Longer Term Exposure to Fine Particulate Air Pollution. *Inhal. Toxicol.* **2007**, *19*, 33–38.

(11) Bell, M. L.; McDermott, A.; Zeger, S. L.; Samet, J. M.; Dominici, F. Ozone and Short-term Mortality in 95 US Urban Communities, 1987−2000. *J. Am. Med. Assoc.* **2004**, *292* (19), 2372–2378.

(12) Bell, M. L.; Dominici, F. Effect Modification by Community Characteristics on the Short-term Effects of Ozone Exposure and Mortality in 98 US Communities. *Am. J. Epidemiol.* **2008**, *167* (8), 986–997.

(13) IPCC. *Special Report on Emissions Scenarios*; Intergovernmental Panel on Climate Change, 2000.

(14) Bell, M. L.; Goldberg, R.; Hogrefe, C.; Kinney, P. K.; Knowlton, K.; Lynn, B.; Rosenthal, J.; Rosenzweig, C.; Patz, A. Climate Change, Ambient Ozone, and Health in 50 US Cities. *Clim. Change* **2007**, *82*, 61–76.

(15) Knowlton, K.; Rosenthal, J. E.; Hogrefe, C.; Lynn, B.; Gaffin, S.; Goldberg, R.; Rosenzweig, C.; Civerolo, K.; Ku, J.-Y.; Kinney, P. L. Assessing Ozone-Related Health Impacts Under a Changing Climate. *Environ. Health Perspect.* **2004**, *112* (15), 1557–1563.

(16) U.S. Climate Change Science Program. *Scientific Assessment of the Effect of Global Change on the United States*; National Science and Technology Council, May 2008; p 182; http://www.climate science.gov/Library/scientific-assessment.

(17) Jacob, D. J.; Winner, D. A. Effect of climate change on air quality. *Atmos. Environ.* **2009**, *43*, 51–63.

(18) Liao, K.-J.; Tagaris, E.; Manomaiphiboon, K.; Napoleok, S. L.; Woo, J.-H.; He, S.; Amar, P.; Russell, A. G. Sensitivity of ozone and fine particulate matter formation to emissions under the impact of potential future climate change. *Environ. Sci. Technol.* **2007**, *41*, 8355–8361.

(19) Byun, D. W.; Schere, K. L. Review of the governing equations, computational algorithms, and other components of the Models-3 Community Multiscale Air Quality (CMAQ) modeling system. *Appl. Mech. Rev.* **2006**, *59*, 51–77.

(20) Rind, D.; Lerner, J.; Shah, K.; Suozzo, R. Use of on-line tracers as a diagnostic tool in general circulation model development: 2. Transport between the troposphere and stratosphere. *J. Geophys. Res.* **1999**, *104*, 9151–9167.

(21) Mickley, L. J.; Jacob, D. J.; Field, B. D.; Rind, D. Effects of future climate change on regional air pollution episodes in the United States. *Geophys. Res. Lett.* **2004**, *31*, L24103.

(22) Grell, G.; Dudhia, J.; Stauffer, D. R. A description of the fifth generation Penn State/NCAR mesoscale model (MM5); Tech. Note NCAR/TN-398+STR; National Center for Atmospheric Research: Boulder, CO, 1994.

(23) Leung, L. R.; Gustafson, W. I., Jr. Potential regional climate and implications to U.S. air quality. *Geophys. Res. Lett.* **2005**, *32*, L16711.

(24) Tagaris, E.; Manomaiphiboon, K.; Liao, K.-J.; Leung, L. R.; Woo, J.-H.; He, S.; Amar, P.; Russell, A. G. Impacts of global climate change and emissions on regional ozone and fine particulate matter concentrations over the United States. *J. Geophys. Res.* **2007**, *112*, D14312.

(25) U.S. EPA. *Air Quality Criteria for Ozone and Related Photochemical Oxidants*; EPA 600/R-05/004aF; Washington, DC, 2006.

(26) U.S. EPA. *Air Quality Criteria for Particulate Matter*; EPA/600/P-99/002aF; Washington, DC, 2004.

(27) U.S. EPA. *Final Regulatory Impact Analysis: $PM_{2.5}$ NAAQS*; Prepared by Office of Air and Radiation, 2006; http://www.epa.gov/ttn/ecas/ria.html.

(28) U.S. EPA. *Final Ozone NAAQS Regulatory Impact Analysis*; Prepared by Office of Air and Radiation, 2008; http://www.epa.gov/ttn/ecas/ria.html.

(29) Schwartz, J. Short term fluctuations in air pollution and hospital admissions of the elderly for respiratory disease. *Thorax* **1995**, *50*, 531–538.

(30) Peel, J. L.; Tolbert, P. E.; Klein, M.; Metzger, K. B.; Flanders, W. D.; Todd, K.; Mulholland, J. A.; Ryan, P. B.; Frumkin, H. Ambient air pollution and respiratory emergency department visits. *Epidemiology* **2005**, *16*, 164–174.

(31) Jaffe, D. H.; Singer, M. E.; Rimm, A. A. Air pollution and emergency department visits for asthma among Ohio Medicaid recipients, 1991−1996. *Environ. Res.* **2003**, *91*, 21–28.

(32) Wilson, A. M.; Wake, C. P.; Kelly, T.; Salloway, J. C. Air pollution and weather, and respiratory emergency room visits in two northern New England cities: an ecological time-series study. *Environ. Res.* **2005**, *97*, 312–321.

(33) Ostro, B. D.; Rothschild, S. Air Pollution and Acute Respiratory Morbidity - an Observational Study of Multiple Pollutants. *Environ. Res.* **1989**, *50*, 238–247.

(34) Chen, L.; Jennison, B. L.; Yang, W.; Omaye, S. T. Elementary school absenteeism and air pollution. *Inhalation Toxicol.* **2000**, *12*, 997–1016.
(35) Gilliland, F. D.; Berhane, K.; Rappaport, E. B.; Thomas, D. C.; Avol, E.; Gauderman, W. J.; London, S. J.; Margolis, H. G.; McConnell, R.; Islam, K. T.; Peters, J. M. The effects of ambient air pollution on school absenteeism due to respiratory illnesses. *Epidemiology* **2001**, *12*, 43–54.
(36) Pope, C. A.; Burnett, R. T.; Thun, M.J.; Calle, E. E.; Krewski, D.; Ito, K.; Thurston, G. D. Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. *J. Am. Med. Assoc.* **2002**, *287*, 1132–1141.
(37) Woodruff, T. J.; Grillo, J.; Schoendorf, K. C. The relationship between selected causes of postneonatal infant mortality and particulate air pollution in the United States. *Environ. Health Perspect.* **1997**, *105*, 608–612.
(38) Abbey, D. E.; Ostro, B. E.; Petersen, F.; Burchette, R. J. Chronic Respiratory Symptoms Associated with Estimated Long-Term Ambient Concentrations of Fine Particulates Less Than 2.5 Microns in Aerodynamic Diameter ($PM_{2.5}$) and Other Air Pollutants. *J. Exposure Anal. Environ. Epidemiol.* **1995**, *5*, 137–159.
(39) Moolgavkar, S. H. Air Pollution and Daily Deaths and Hospital Admissions in Los Angeles and Cook Counties. In *Revised Analyses of Time-Series Studies of Air Pollution and Health*; Health Effects Institute: Boston, MA, May 2003; pp 183−198.
(40) Ito, K. Associations of Particulate Matter Components with Daily Mortality and Morbidity in Detroit, Michigan. In *Revised Analyses of Time-Series Studies of Air Pollution and Health*; Health Effects Institute: Boston, MA, May 2003; pp 183−198.
(41) Ostro, B. D.; Lipsett, M. J.; Wiener, M. B.; Selner, J. C. Asthmatic Responses to Airborne Acid Aerosols. *Am. J. Public Health* **1991**, *81*, 694–702.
(42) Vedal, S.; Petkau, J.; White, R.; Blair, J. Acute effects of ambient inhalable particles in asthmatic and nonasthmatic children. *Am. J. Respir. Crit. Care Med.* **1998**, *157*, 1034–1043.
(43) Dockery, D. W.; Cunningham, J.; Damokosh, A. I.; Neas, L. M.; Spengler, J. D.; Koutrakis, P.; Ware, J. H.; Raizenne, M.; Speizer, F. E. Health Effects of Acid Aerosols On North American Children - Respiratory Symptoms. *Environ. Health Perspect.* **1996**, *104*, 500–505.
(44) Pope, C. A.; Dockery, D. W.; Spengler, J. D.; Raizenne, M. E. Respiratory Health and PM_{10} Pollution - a Daily Time Series Analysis. *Am. Rev. Respir. Dis.* **1991**, *144*, 668–674.
(45) Schwartz, J.; Neas, L. M. Fine particles are more strongly associated than coarse particles with acute respiratory health effects in schoolchildren. *Epidemiology* **2000**, *11*, 6–10.
(46) Weaver, C. P. et al. A preliminary synthesis of modeled climate change impacts on U.S. regional ozone concentrations. Bull. Am. Meteorol. Soc. under review.
(47) Prinn, R.; Jacoby, H.; Sokolov, A.; Wang, C.; Xiao, X.; Yang, Z.; Eckhaus, R.; Stone, P.; Ellerman, D.; Melillo, J.; Fitzmaurice, J.; Kicklighter, D.; Holian, G.; Liu, Y. Integrated global system model for climate policy assessment: Feedbacks and sensitivity studies. *Clim. Change* **1999**, *41*, 469–546.
(48) Reilly, J.; Prinn, R.; Harnisch, J.; Fitzmaurice, J.; Jacoby, H.; Kicklighter, D.; Melillo, J.; Stone, P.; Sokolov, A.; Wang, C. Multi-gas assessment of the Kyoto Protocol. *Nature* **1999**, *401*, 549–555.
(49) Liao, K.-J.; Tagaris, E.; Manomaiphiboon, K.; Wang, C.; Woo, J.-H.; He, S.; Amar, P.; Russell, A. G. Climate Impacts on Air Quality Response to Controls: Not Such an Uncertain Future. *Atmos. Chem. Phys.* **2009**, *9*, 865–878.

ES803650W