

Climate change, ambient ozone, and health in 50 US cities

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Abstract We investigated how climate change could affect ambient ozone concentrations and the subsequent human health impacts. Hourly concentrations were estimated for 50 eastern US cities for five representative summers each in the 1990s and 2050s, reflecting current and projected future climates, respectively. Estimates of future concentrations were based on the IPCC A2 scenario using global climate, regional climate, and regional air quality models. This work does not explore the effects of future changes in anthropogenic emissions, but isolates the impact of altered climate on ozone and health. The cities' ozone levels are estimated to increase under predicted future climatic conditions, with the largest increases in cities with present-day high pollution. On average across the 50 cities, the summertime daily 1-h maximum increased 4.8 ppb, with the largest increase at 9.6 ppb. The average number of days/summer exceeding the 8-h regulatory standard increased 68%. Elevated ozone levels correspond to approximately a 0.11% to 0.27% increase in daily total mortality. While actual future ozone concentrations depend on climate and other influences such as changes in emissions of anthropogenic precursors, the results presented here

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indicate that with other factors constant, climate change could detrimentally affect air quality and thereby harm human health.

1 Introduction

Climate change could harm human health in many ways, including adverse changes in food production (Rosenzweig et al. 2001), malaria (Loevinsohn 1994; Tanser et al. 2003), dengue fever (Hales et al. 2002), thermal stress (Martens 1998), aeroallergens (Beggs 2004), extreme events (Ikeda et al. 2005; Knutson et al. 1998), waterborne diseases (Casman et al. 2001; Charron et al. 2004), and other diseases (Epstein 2001; Hunter 2003; Patz et al. 2005; Reiter 1998). Changes in climate could also affect health by increasing the concentrations of outdoor air pollutants (Bernard et al. 2001; Haines and Patz 2004; Knowlton et al. 2004; McMichael and Githeko 2001). A recent study of ozone-related health impacts from climate change in 31 counties in New York projected a median 4.5% increase in ozone-related acute summer mortality by the 2050s, as compared to the 1990s (Knowlton et al. 2004). Tropospheric ozone is particularly sensitive to climate change because the chemical reactions that form ozone are temperature dependent, with higher levels of ozone produced during warmer time periods (Aw and Kleeman 2003; Seinfeld and Pandis 2006; Sillman and Samson 1995). Interannual variability in ozone levels is related to summer weather conditions for this region. For example, low ozone levels during the summer of 2003 were largely attributable to favorable (cool and wet) weather conditions across much of the United States (USEPA 2004). Further, biogenic emissions of volatile organic compounds (VOCs), which are precursors to ozone, increase with rising temperature (Constable et al. 1999). These natural emissions of VOCs constitute a significant fraction of total VOCs, and in some areas exceed anthropogenic sources (Fuentes et al. 2000).

Ozone levels have generally declined in the United States since the enactment of the Clean Air Act in 1970 due to emission control programs. However, high ozone concentrations persist with many areas still having levels above the health-based National Ambient Air Quality Standards (NAAQS). Currently, over 100 million people in the US reside in areas with ozone concentrations exceeding the 8-h regulatory standard (USEPA 2004). An increase in ozone concentrations, induced by climate change, would add to this already present health burden, which has been associated with higher levels of hospital admissions, respiratory symptoms, impaired lung development, and mortality, among other adverse health responses (Anderson et al. 2004; Bell et al. 2005; Dockery and Pope 1994; Gaudermann et al. 2002; Levy et al. 2001; Lippman 1989; Steib et al. 2002, 2003; Thurston and Ito 1999, 2001; USEPA 2006). Further, because of fossil fuel combustion, climate change control policies can have short-term benefits to local air quality, and thereby human health, in addition to their effects on long-term climate change and health (Bell et al. 2006; Cifuentes et al. 2001a,b).

We investigated how climate change could affect ozone levels and the subsequent changes in health impacts for 50 cities in the eastern US. A model of future climate change and a linked air pollution modeling system were used to compare ozone levels for current and potential future climatic conditions during the summer months (June, July, and August) for the 1990s and 2050s. In addition to meteorological variables such as temperature, wind speed, and wind direction that may change in a future climate, air quality conditions also depend on anthropogenic and biogenic emissions of ozone precursors, which in turn are a function of numerous factors such as population growth, energy demand, transportation

networks, land-use, fuel type, and pollution control technology. In order to explore the effect of climate change alone, this work isolates the response of tropospheric ozone concentrations to changes in climate, without regard to changes in anthropogenic emissions.

The human health consequences of ozone can be estimated through the change in health endpoints as identified by concentration-response functions from epidemiological studies. Other measures include exceedances of regulatory standards, such as the primary NAAQS, which were established to protect human health with an adequate margin of safety (USEPA 1997), and changes in the Air Quality Index (AQI), which is intended to give an overall assessment of the health impacts of a particular day's pollution levels (USEPA 2003). In this study, we utilize these measures to estimate the range of the potential human health consequences corresponding to altered ozone concentrations under a future climate scenario.

2 Methods

2.1 Estimates of ozone concentrations

Hourly ambient concentrations of ground-level ozone were estimated for each of 50 cities for June 1 to August 31 for 1993 to 1997 to represent the current climate, and for the summers of 2053 to 2057 to represent the future climate under the Intergovernmental Panel on Climate Change (IPCC) A2 scenario. The simulations account for climate change-induced alterations in the chemical reaction rates for tropospheric ozone formation and temperature-related changes in the emissions of biogenic ozone precursors (Hogrefe et al. 2004a), however the anthropogenic emission inventory is held constant. The climate and air quality simulations and the IPCC A2 emissions scenario are described in more detail below.

A linked climate/air quality modeling system developed by the New York Climate and Health Project (Hogrefe et al. 2004a,b; Knowlton et al. 2004) was used to derive ozone concentrations for each of 4,012 gridcells in each vertical layer in a domain with 36-km horizontal resolution for the eastern US. In this study, we utilize these simulations by interpolating the gridded concentration fields for the surface layer to the location of 50 cities in the eastern US. The modeling system included the Goddard Institute for Space Studies (GISS) general circulation model (GCM) (Russell et al. 1995), the PSU/NCAR mesoscale model (MM5) regional meteorological model (Grell et al. 1994), the Community Multiscale Air Quality (CMAQ) air quality model (Byun and Ching 1999), and the Sparse Matrix Operator Kernel Emissions (SMOKE) emissions processor (Houyoux et al. 2000). The climate effects of the A2 greenhouse gas (GHG) emissions scenario were simulated with the MM5 regional meteorological model driven by the GISS GCM; ozone pollution effects were simulated using the CMAQ air quality model for five summers in the 1990s; and model results were validated for current climate and air quality conditions (Grell et al. 1994; Hogrefe et al. 2004b; Russell et al. 1995).

Model evaluation included comparison of model estimates to observations for overall patterns and values and for variability. For example, evaluation of the meteorological model compared model-predicted meteorological fields, such as surface temperature, clouds, and winds, to observations. Comparisons used several approaches, including spectral decomposition, synoptic typing analysis, and use of cumulative distribution functions to estimate variability. The air quality model evaluation demonstrated that the model provides realistic estimates of the pattern of the daily maximum 1-h concentration over the 1993 to 1997 summers. The bias of estimated and observed concentrations was <1 ppb. The coupled MM5/

CMAQ modeling system produced reasonable estimates of mean ozone levels, signifying that emissions and synoptic-scale meteorology are well represented in the system (Hogrefe et al. 2004b). Further details on the modeling system, evaluation, and its application are available elsewhere (Hogrefe et al. 2004a,b; Lynn et al. 2004).

Climate and ozone concentrations for June, July, and August in the 2050s were simulated with the linked models. Projected future ozone concentrations were compared to those of the 1990s, holding constant all other human contributions to ozone pollution. Average summertime temperatures for the eastern US were projected to rise by 1.6 to 3.2 °C for these 50 cities from the 1990s to the 2050s.

The IPCC established several scenarios of GHG emissions for use in modeling studies. These emissions scenarios differ based on estimates of population, technology, economic growth, and other factors (Nakicenovic and Swart 2000). The modeling simulations analyzed in this study used the IPCC A2 climate scenario, one of the scenarios with the highest growth of carbon dioxide among all IPCC scenarios. This scenario is characterized by a steady increase in carbon dioxide emissions, a fuel mix determined by regional resource availability, a shift towards post-fossil fuel technologies in high-income but resource poor regions, reliance on older fossil fuel technology in lower-income resource-rich regions, and a worldwide population at 15 billion by 2100 (Nakicenovic and Swart 2000). This scenario assumes that decision makers place little emphasis on environmental concerns, however it does include control of GHGs that impact local air quality and controls on pollutants that affect water availability, soil quality, and agricultural productivity.

A complete picture of future ozone concentrations would require exploration of an extensive list of potential changes including regulatory controls, population growth, energy use patterns, and energy technologies. This work isolates the impact of climatic changes on ozone, and does not explore future changes in the emissions of anthropogenic precursors. In other words, this research investigates what modern day ozone levels might look like under a projected future climatic scenario. To fully gauge the range of potential ozone concentrations and related health consequences, a wide variety of scenarios would need to be explored.

2.2 Health and regulatory impacts

We calculated exceedances of the 1- and 8-h health-based regulatory standards for ozone, which differs from non-attainment of these standards (USEPA 1997). An exceedance day occurs when ozone levels go above the regulatory standard, and concentrations may be rounded down so that exceedances of the 1- and 8-h standards are above 124 and 84 parts per billion (ppb), respectively. ‘Attainment’ of the legal requirement is calculated using several years of data. In other words, an area could exceed the regulatory standard on a given day, but still be in attainment with the standard, depending on the concentrations of other days. However, an increase in the number of exceedance days would likely bring more areas into non-attainment status.

We also calculated what fraction of the summer days would fall under each category of the AQI for ozone. The AQI is used to provide an overall assessment of the health impacts of outdoor air with respect to several pollutants (USEPA 2003). The daily AQI is determined by assigning an individual index to each of several pollutants: ozone (8- and 1-h averages); particulate matter (PM₁₀ and PM_{2.5}); carbon monoxide, sulfur dioxide, and nitrogen dioxide. The highest of these individual indices is assigned as the overall AQI for that day. Thus, while the AQI is representative of air pollutant levels, it does not provide an overall picture of air quality. The AQI can range from 0 to 500, with 0 representing the best air quality and 500 the worst. The AQI health-related levels for ozone are listed in Table 1.

Table 1 Air Quality Index (AQI) levels for ozone (modified from (USEPA 2003))

AQI	Ozone 8-h (ppb)	Ozone 1-h (ppb)	Air quality	Color code	Health advisory
0 to 50	0 to 64	0 to 84	Good	Green	None
51 to 100	65 to 84	85 to 124	Moderate	Yellow	Unusually sensitive people should consider limiting prolonged outdoor exertion
101 to 150	85 to 104	125 to 164	Unhealthy for sensitive groups	Orange	Active children and adults, and people with respiratory disease, such as asthma, should limit prolonged outdoor exertion
151 to 200	105 to 124	165 to 204	Unhealthy	Red	Active children and adults, and people with respiratory diseases, such as asthma, should avoid prolonged outdoor exertion; everyone else, especially children, should limit prolonged outdoor exertion
201 to 300	125 to 374	205 to 404	Very unhealthy	Purple	Active children and adults, and people with respiratory disease, such as asthma, should avoid all outdoor exertion; everyone else, especially children should limit outdoor exertion
301 to 500	375+	405+	Hazardous	Maroon	Everyone should avoid physical activity outdoors due to emergency pollution conditions

Health advisories in the form of ozone alert days are evaluated from forecasted ozone concentrations. An ozone ‘advisory’ is issued when the ozone forecast has an orange AQI, whereas an ozone ‘alert’ is declared when the ozone forecast has a red AQI. An ozone health ‘alert’ is issued for code purple, however this is a rare occurrence.

Concentration-response functions from epidemiological studies were used to provide an approximation of the changes in mortality and hospital admissions rates corresponding to changes in ozone levels from the 1990s to the 2050s. Because epidemiological studies differ in their estimated concentration-response functions, we calculated health impact estimates from multiple epidemiological studies. The concentration-response functions for a specific health endpoint can vary due to data availability, statistical methods, the communities’ underlying health status, and other factors. In the future, the relationship between ambient pollution levels and health effects may change, for example due to changes in daily activity patterns and health care systems. Still, the present day relationships between ozone and health can provide a useful gauge of the health impacts that may occur with future changes in air quality. We choose epidemiological studies based on US cities (Bell et al. 2004, 2005; Levy et al. 2001; Medina-Ramón et al. 2006; Moolgavkar et al. 1997; Schwartz 1994, 1995, 2005; Shepard 2003; Stieb et al. 2002, 2003; Thurston and Ito 2001).

3 Results

3.1 Ozone concentrations

Under the IPCC A2 climate scenario, the simulated daily 1- and 8-h maximum ozone levels during the summer are projected to rise 4.8 and 4.4 ppb, respectively, from the 1990s to the 2050s, averaged over the 50 cities. For comparison, Hogrefe et al. (2004a) reported an

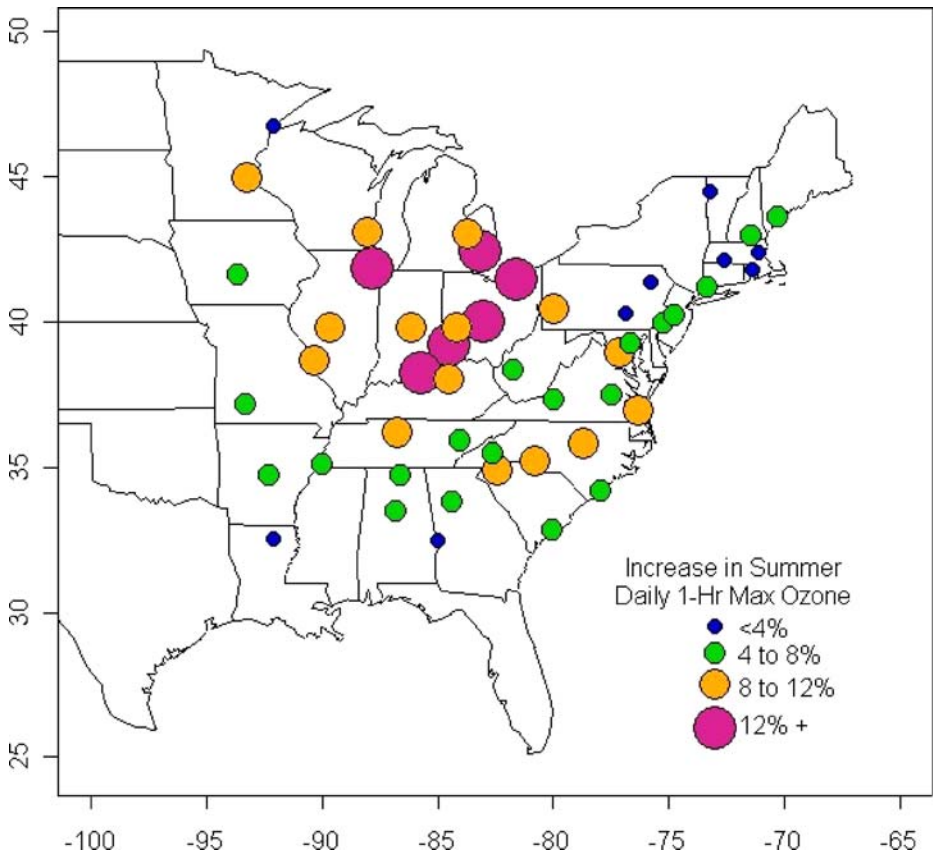


Fig. 1 Increase in summertime daily 1-h maximum ozone concentrations (from 1990s to 2050s)

increase of 4.2 ppb for summertime average 8-h daily maximum ozone concentrations averaged over 428 ozone monitors in the modeling domain for the same simulation.

The increases in ozone levels showed substantial spatial variation, as shown by Fig. 1. Table 2 provides the increase in ozone levels for several concentration metrics and shows the largest and smallest increase for any of the 50 cities. The future climate scenario caused higher daily 1-h maximum and daily 8-h maximum ozone concentrations for all cities. The daily average for all cities was also raised under the climate change scenario, except for one city that had basically the same daily average (0.01 ppb lower for the climate change scenario than the current emissions scenario).

Table 2 Changes in summer ozone concentrations comparing the projected future climate (2050s) to current climate (1990s), for 50 eastern US cities

	Average increase	Smallest increase ^a	Largest increase ^a
Daily average	2.9 ppb (6.4%)	-0.01 ppb (-0.02%)	6.4 ppb (13.1%)
Daily 1-h max	4.8 ppb (7.4%)	0.51 ppb (0.8%)	9.6 ppb (14.3%)
Daily 8-h max	4.4 ppb (7.2%)	0.45 ppb (0.8%)	9.0 ppb (13.7%)

^a The smallest and largest city-specific effect represents the change averaged across all summers for any single city.

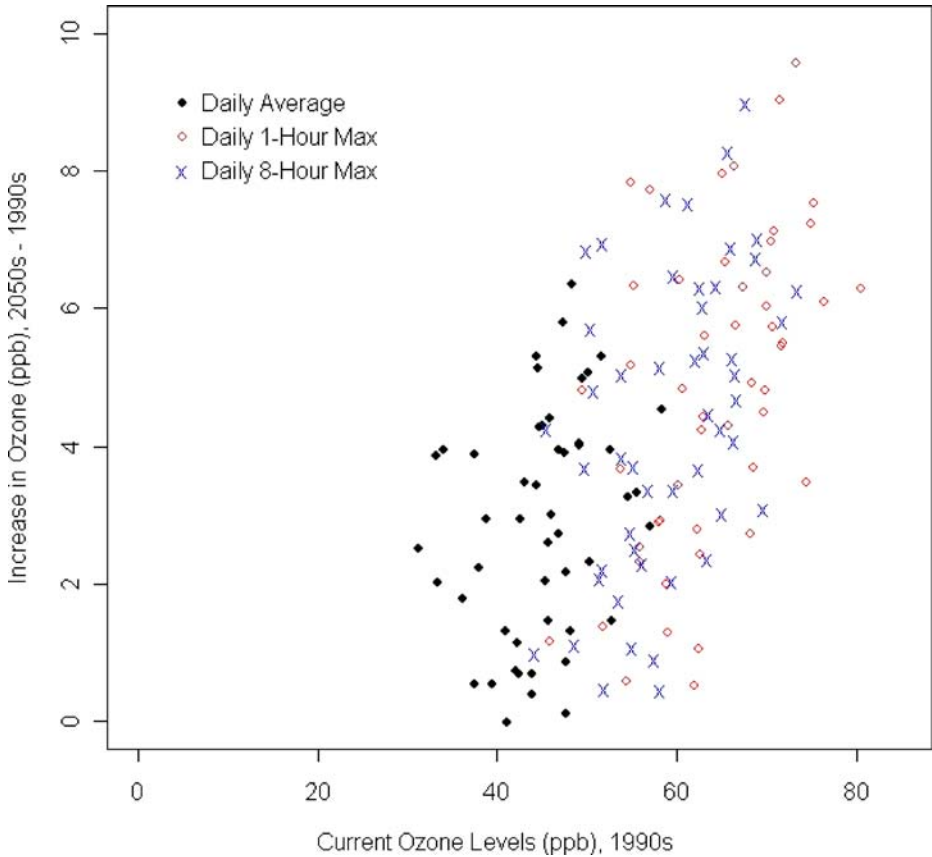


Fig. 2 Summer ozone concentrations under the current climate scenario (1990s) and increases under the future A2 climate scenario (2050s)

Cities that already experience elevated ozone levels under the current climatic conditions are predicted to exhibit the largest increases in ozone in the projected future climate scenario (Fig. 2). The higher increases in ozone for areas with present-day high pollution levels may result from these regions' correspondingly high emissions of ozone precursors, such as transportation and industrial pollution, as well as possibly biogenic emissions. The correlation between the increase in ozone and the baseline 1990s ozone levels is 0.55. The increase in ozone levels for each city was not purely caused by the increase in temperature for that city; other factors such as changes in biogenic emissions and changes in circulation patterns and mixing heights also played a role. This is demonstrated in Fig. 3, which shows the increase in the daily average ozone summer levels as a function of the increase in temperature. The correlation between the increase in summer temperature and the increase in ozone is 0.2.

3.2 Regulatory exceedances

We calculated the number of NAAQS exceedance days for each of the 10 summers for each city, using both the 1- and 8-h NAAQS standards, to estimate how the anticipated number of exceedance days would differ under the projected future climate scenario. All cities had

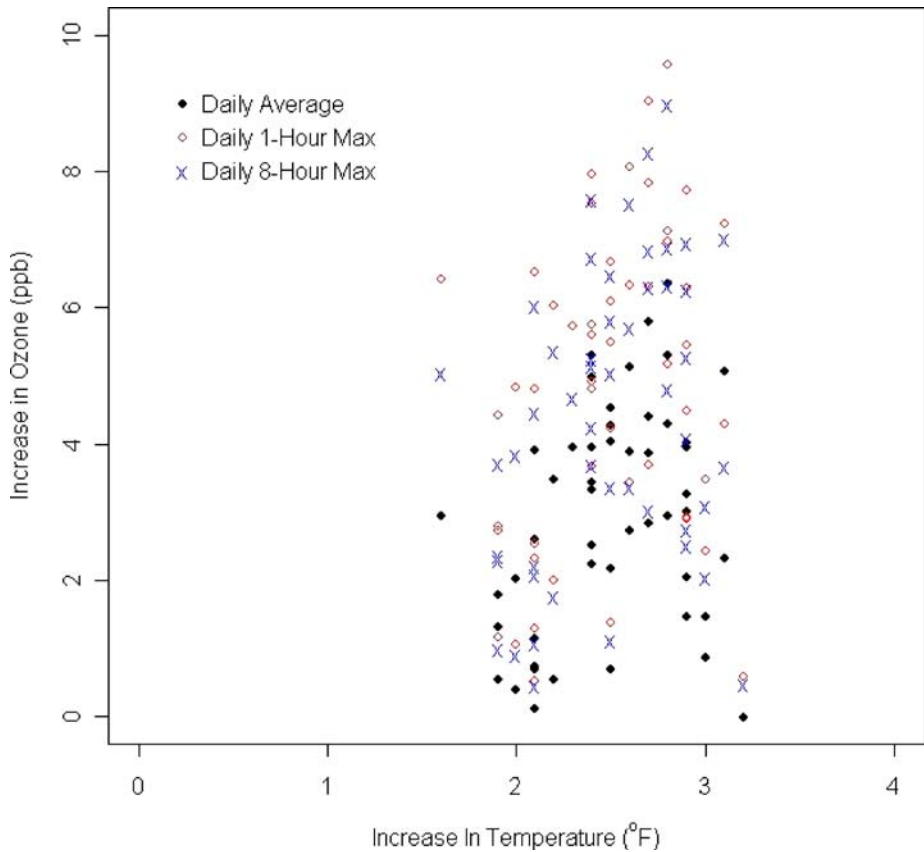


Fig. 3 Increases in temperature and summer ozone concentrations comparing the current climate scenario (1990s) to the future A2 climate scenario (2050s)

more or the same number of exceedance days under the projected future climate than under the current climate scenario for both regulatory standards. Figures 4 and 5 depict the average number of exceedance days per summer for each city for the 1- and 8-h ozone NAAQS, respectively. The blue horizontal bars represent the average number of exceedance days per summer for the current climate, whereas the red bars represent the additional number of exceedance days that would occur under the projected future climate scenario.

For both the present-day and projected future climate scenarios, all cities had the same number or more 8-h NAAQS exceedance days as 1-h NAAQS exceedance days. This is anticipated given that the 8-h standard is generally more stringent than the 1-h requirement (Bell and Ellis 2003). Cities with higher pre-existing ozone levels exhibited the largest increases in the number of exceedance days.

For the 1-h NAAQS, most cities (37) had no simulated 1-h NAAQS exceedance days under the current climate. However, because of model biases (Hogrefe et al. 2004b) the simulated current climate scenario ozone estimates do not represent actual ozone quality with respect to the NAAQS. For example, Greenville, SC, Nashville, and Roanoke are currently in non-attainment for the 1-h ozone standard although no 1-h exceedance days were estimated for the five 1990's summers (USEPA 2006). Sixteen of these 37 cities with

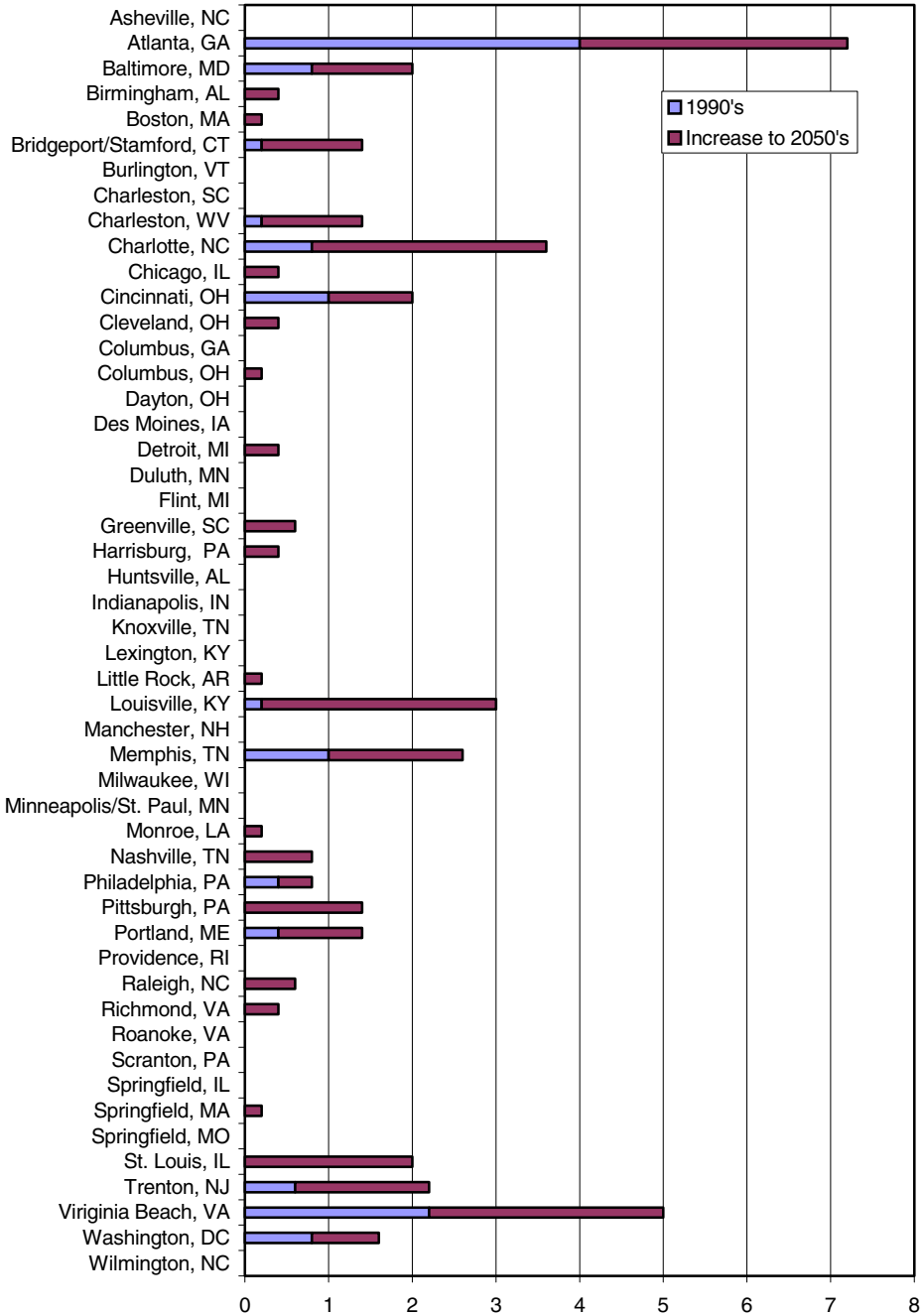


Fig. 4 Average number of 1-h ozone NAAQS exceedance days/summer

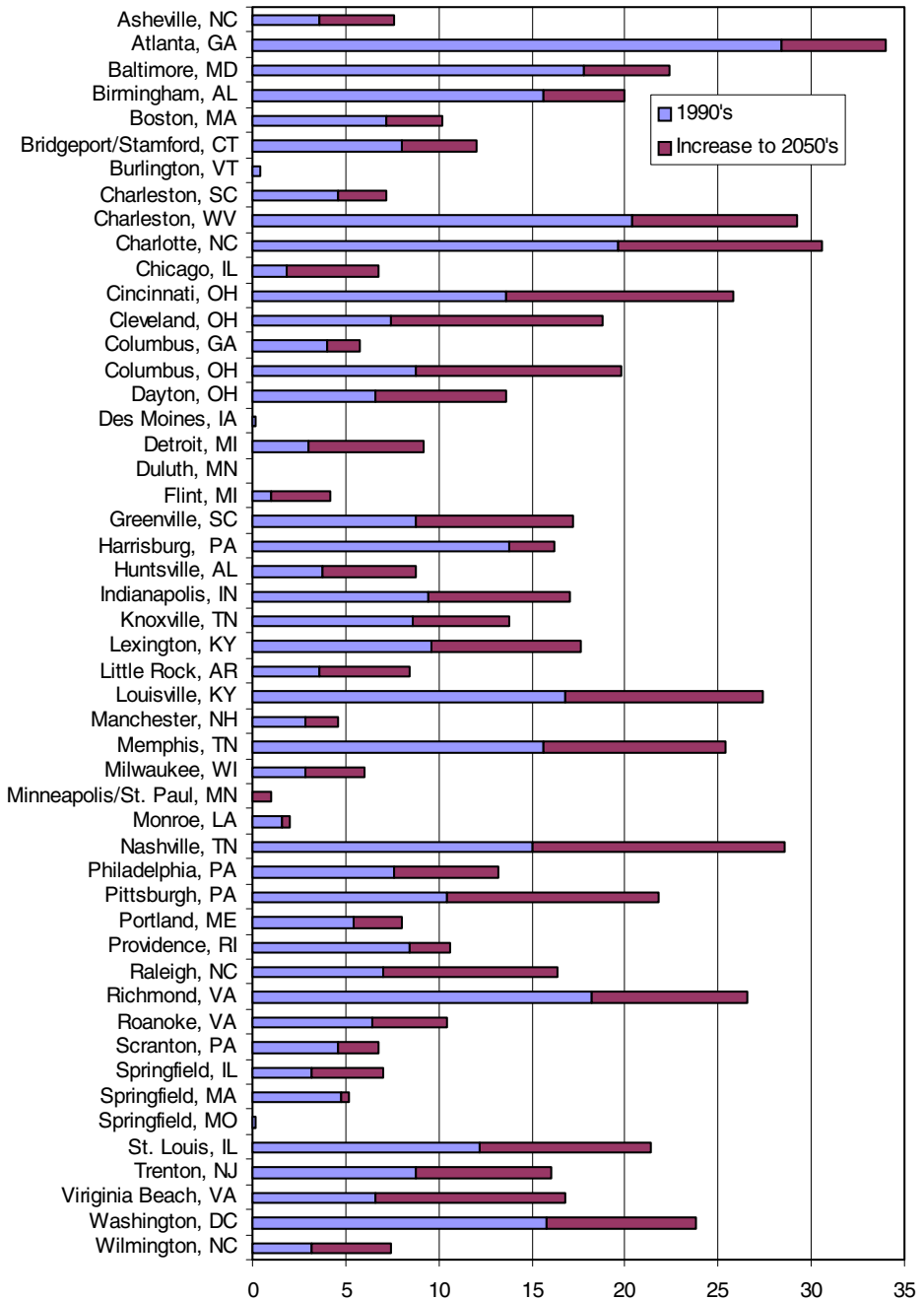


Fig. 5 Average number of 8-h ozone NAAQS exceedance days/summer

no simulated 1-h NAAQS exceedances in the current summers exceeded the 1-h requirement under projected future climatic conditions in the 2050s. On average across all the cities, there are an estimated 0.6 more exceedance days per summer in the 2050s than in the 1990s summers. For areas that exceeded the requirement for the 1990s summers, an average 1.7 more exceedance days/summer are predicted. The largest increase was 3.2 more 1-h exceedance days/summer for the city with the highest number of exceedance days/summer under the present day climate.

For the 8-h NAAQS, only two cities had no simulated 8-h exceedance days under the current climate, however one of these did exceed the standard using projected future climatic conditions. On average across all cities, there were 5.5 more 8-h NAAQS exceedance days/summer with the projected future climate than with the current climate, which is a 68% increase. In their analysis of simulated changes in the number of 8-h ozone NAAQS exceedances at the location of 428 O₃ monitors in the modeling domain, Hogrefe et al. (2004a) reported an increase of such exceedances by 65% from the 1990s to the 2050s.

3.3 Ozone action days

Figure 6 depicts the percent of summer days under each AQI ozone category for current conditions and the A2 projected future climate scenario, on average across the 50 cities. No city had maroon levels, the worst category, under either current or projected future conditions. Even under the current climate, 37% of the summer days in these 50 cities had an ozone AQI of yellow or worse, and 9% of the days had unhealthy conditions with an ozone AQI of orange or worse. Under the A2 climate change scenario for the 2050s, 47% of the days had yellow or worse ozone AQIs and 16% were at orange or worse categories, on average across the cities. The climate change scenario altered the distribution of AQI categories, with more days in each of the categories with adverse health effects (yellow, orange, red, and purple) and fewer days in the good ozone level category (green).

All cities had the same or more days with unhealthy ozone levels in the projected future climate. Several cities without red or higher AQI levels in the current scenario reach red

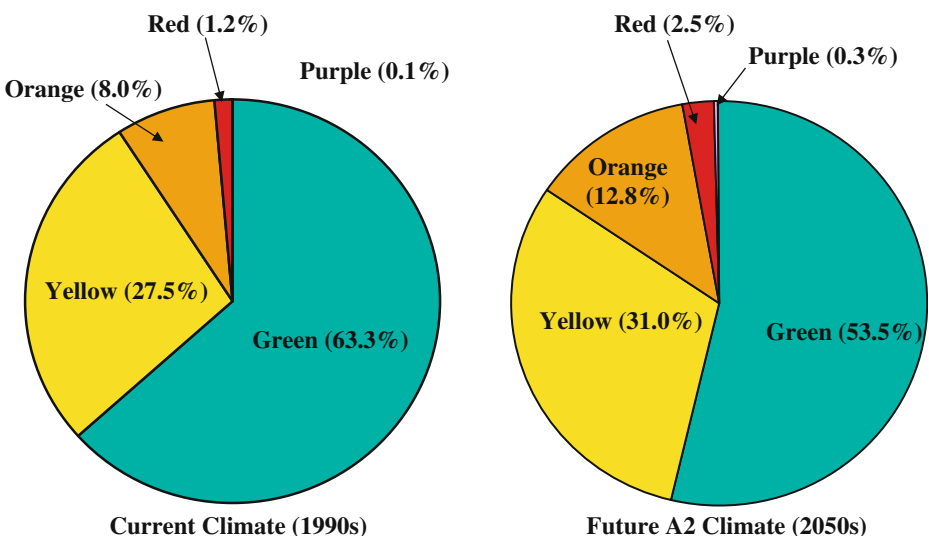


Fig. 6 Percent of summer days in each ozone air quality index category, on average across the 50 cities

Table 3 Percent increase (95% confidence intervals) from the 1990s to the 2050s in cause-specific hospital admissions

	Average across all cities	Largest city-specific effect ^a	Epidemiological study	Age category
COPD	0.8% (-0.2, 1.8)	1.8% (-0.4, 3.96)	[Moolgavkar et al. 1997]	≥65
	1.6% (0.4, 2.8)	3.5% (0.9, 6.27)	[Schwartz 1994]	≥65
	0.24% (0.07, 0.41)	0.49% (0.14, 0.85)	[Medina-Ramón et al. 2006]	≥65
Respiratory	0.8% to 2.1%	1.7% to 4.6%	[Schwartz 1995]	≥65
Asthma	2.1% (0.6, 3.6)	4.7% (1.4, 8.1)	[Sheppard 2003]	≤64

^a The largest city-specific effect represents the largest change averaged across all summers for any single

levels with the projected future climate (Asheville, Chicago, Columbus, GA, Detroit, Flint, Little Rock, Raleigh, Springfield, IL, and Springfield, MA). Ten cities without purple AQIs in the current scenario have those levels under projected future climatic conditions (Boston, Harrisburg, Louisville, Nashville, Philadelphia, Pittsburgh, Portland, ME, Richmond, St. Louis, and Trenton).

3.4 Human health impacts

The increase in ozone concentrations resulting from climate change would be accompanied by a rise in the associated adverse health effects, such as premature death, hospital admissions and emergency department visits, exacerbation of asthma, and decreased lung function (Dockery and Pope 1994; Lippmann 1989, 1993; Thurston and Ito 1999; USEPA 2006). We estimated the change in selected health endpoints from elevated ozone levels caused by climate change using concentration-response relationships derived from epidemiological studies (Bell et al. 2004, 2005; Levy et al. 2001; Medina-Ramón et al. 2006; Moolgavkar et al. 1997; Schwartz 1994, 1995, 2005; Sheppard 2003; Stieb et al. 2002, 2003; Thurston and Ito 2001).

Table 4 Percent increase (95% confidence interval) from the 1990s to the 2050s in total mortality from elevated ozone levels in response to climate change

	Average across all cities	Largest city-specific effect ^a	Epidemiological study
Total	0.15% (0.08, 0.22)	0.33% (0.17, 0.48)	[Bell et al. 2004] ^b
	0.11% (0.005, 0.21)	0.22% (0.01, 0.42)	[Schwartz 2005] ^c
	0.24% (0.15, 0.32)	0.53% (0.34, 0.71)	[Bell et al. 2005]
	0.27% (0.16, 0.38)	0.63% (0.38, 0.88)	[Levy et al. 2001]
	0.21% (0.06, 0.37)	0.43% (0.12, 0.73)	[Stieb et al. 2002, 2003]
	0.26% (0.15, 0.37)	0.52% (0.30, 0.75)	[Thurston and Ito 2001]
Cardiovascular	0.31% (0.20, 0.42)	0.68% (0.43, 0.92)	[Bell et al. 2005]
Respiratory	0.12% (-0.14, 0.38)	0.27% (0.00, 0.85)	[Bell et al. 2005]
Cardiovascular and respiratory	0.18% (0.09, 0.28)	0.41% (0.20, 0.62)	[Bell et al. 2004] ^b

^a The largest city-specific effect represents the largest change averaged across all summers for any city.

^b These results use concentration-response functions derived from a multi-city time-series study. Other results are from meta-analyses, except where specified.

^c These results use concentration-response functions derived from a multi-city case-crossover study. Other results are from meta-analyses, except where specified.

Table 3 provides the percent increase in hospital admissions for persons aged 65 and over for chronic obstructive pulmonary disease (COPD) and respiratory causes, and for those aged 64 and younger for asthma-related causes. Results are provided for the average increase in cause-specific hospital admissions across all the cities, and the largest city-specific effect. The 95% confidence intervals reflect uncertainty in the concentration-response functions from the epidemiological studies, not uncertainty relating to the climate change predictions.

We estimated the percent increase in non-accidental mortality for all causes (total mortality) and for cardiovascular and respiratory mortality for these 50 cities based on elevated ozone levels from climate change using several epidemiological studies (Table 4). The actual number of deaths corresponding to these percent increases will depend on the true population and mortality rates in the 2050s. The percent increase in mortality shows some variation in relation to the concentration-response functions derived from various time-series studies. The epidemiological studies for mortality include meta-analysis studies (Bell et al. 2005; Levy et al. 2001; Stieb et al. 2002, 2003; Thurston and Ito 2001), a multi-city time-series study (Bell et al. 2004), and a multi-city case-crossover study (Schwartz 2005). Variation in the concentration-response functions for mortality may be due in part to publication bias in the meta-analysis studies.

4 Discussion

Our findings indicate that recently reported (Hogrefe et al. 2004a) potential increases in tropospheric ozone due to climate change would be accompanied by rises in the health outcomes associated with ozone for these 50 cities, including an increase in total, cardiovascular, and respiratory mortality; hospital admissions for asthma; and hospital admissions for COPD and respiratory causes for older populations. Even at current levels, much of the US is not in compliance with the health-based regulatory requirements for ozone.

The mortality and hospital admission impacts represent only a fraction of the health toll that would be caused by elevations in tropospheric ozone levels. For mortality, the concentration-response functions account for acute exposure and thereby could underestimate the total effect of ozone on mortality through long-term exposure. Other health endpoints include respiratory symptoms such as shortness of breath, restricted activity days, school absenteeism, emergency room visits, asthma attacks, and lung inflammation, in addition to ecological and welfare effects such as material damage (USEPA 1999).

The results presented here reflect the impact of an altered climate on ozone and human health with anthropogenic emissions held constant, however a full portrayal of the possibilities for future ozone levels would include an array of scenarios for anthropogenic emissions of ozone precursors as well as a variety of climate change scenarios based on GHG emissions. Several policies are underway on national and local levels to lower ozone concentrations. Examples are EPA's Clean Air Interstate Rule (CAIR) and city-level actions in transportation planning. Results revealed that the largest increases in ozone levels are predicted to occur in cities that already have high pollution levels, however it may be these cities that work more diligently to lower emissions of ozone precursors in the future. The results presented here indicate that such locations may have to increase their emission control efforts to counteract the adverse impact of climate change on ozone concentrations.

On a larger scale, we could envision different results from various IPCC scenarios. For instance, the A1 scenario has rapid economic expansion, a low population rise, and increased introduction and use of energy efficient technologies. The A2 scenario applied

here has more regionally oriented economic development with slower per capita economic expansion and technological advancement (Nakicenovic and Swart 2000). Due to the range of options for population growth, energy technologies, and policies on local, regional, and global scales, the prediction of ozone levels in the 2050s is quite difficult (Kinney et al. 2005; Schwartz et al. 2005]. In this work, we aim to demonstrate the application of a modeling system to a specific scenario in order to evaluate future ozone levels under conditions of climate change, however various emissions scenarios could result in different ozone levels. Future work will examine a broader range of scenarios.

Another caveat of this work is uncertainty in the various stages of the modeling system. For example, cloud cover may be altered in a future climate, which could affect ozone formation. A recent study estimated changes in low-level cloud cover over the continental US leading to elevated ozone formation for a future climate scenario (Murazaki and Hess 2006). However, the authors noted that the nature of clouds under a future climate scenario is highly uncertain (Murazaki and Hess 2006; Stocker 2001).

The adverse health impacts from ozone in relation to climate change, as well as the many other potential health consequences of climate change such as altered distribution patterns for vector-borne diseases, highlight the need for diligence regarding policies that control greenhouse gas emissions and that improve regional air quality. Such policies can have short-term local benefits to air quality, and thereby human health, in addition to their effects on long-term climate change and health. Thus, it would be worthwhile to incorporate climate concerns into air quality planning, and similarly to consider the short-term health benefits of climate-change mitigation and adaptation policies.

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