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Ozone-related asthma emergency department visits in the US in a warming climate

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Abstract

Ozone exposure is associated with higher risk of asthma-related emergency department visits. The meteorological conditions that govern ozone concentration are projected to be more favorable to ozone formation over much of the United States due to continued climate change, even as emissions of anthropogenic ozone precursors are expected to decrease by 2050. Our goal is to quantify the health benefits of a climate change mitigation scenario versus a “business-as-usual” scenario, defined by the United Nations Intergovernmental Panel on Climate Change Representative Concentration Pathways (RCPs) 4.5 and 8.5, respectively, using the health impact analytical program Benefits Mapping and Analysis Program – Community Edition (BenMAP – CE) to project the number of asthma ED visits in 2045–2055. We project an annual average of 3100 averted ozone-related asthma ED visits during the 2045–2055 period under RCP4.5 versus RCP8.5, with all other factors held constant, which translates to USD \$1.7 million in averted costs annually. We identify counties with tens to hundreds of avoided ozone-related asthma ED visits under RCP4.5 versus RCP8.5. Overall, we project a heterogeneous distribution of ozone-related asthma ED visits at different spatial resolutions, specifically national, regional, and county levels, and a substantial net health and economic benefit of climate change mitigation.

Keywords: ozone, asthma, emergency department visit, climate change

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1. Introduction

Ground-level ozone (O_3) is an established trigger for exacerbating asthma and is associated with higher rates of emergency department (ED) visits for asthma (Zheng et al. 2015; Strickland et al. 2010). Ground-level ozone is formed by the reaction of two classes of air pollutant – nitrogen oxides and volatile organic compounds, known as “precursor” chemicals – which have both natural and anthropogenic sources. The formation of ozone from these primary pollutants is highly dependent on heat and sunlight, such that more ozone is formed in the presence of higher temperatures and greater solar radiation. While emissions of anthropogenic ozone precursors are expected to decrease between now and 2050 (“Emissions Inventory for Air Quality Modeling Technical Support Document: Heavy-Duty Vehicle Greenhouse Gas Phase 2 Final Rule” 2016), for a given level of anthropogenic ozone precursor emissions, near-surface ozone concentrations are expected to increase by mid-century due to continued climate change, a concept called the “climate penalty” (Wu et al. 2008; Nolte CG et al. 2018). As global temperatures continue to rise, ground-level ozone concentrations will be higher than what would be expected based on a reduction of precursor pollutants. Given the abundant evidence of climate change contributing to ozone formation and the effect of ozone on asthma, the impact of continued climate change on ozone-related asthma ED visits, a key marker for poor asthma control and a predictor of mortality, may be pronounced (Virchow et al. 2015; Camargo, Rachelefsky, and Schatz 2009).

The rate of atmospheric warming depends on the pace of global greenhouse gas emissions. The United Nations Intergovernmental Panel on Climate Change (IPCC) developed various climate change scenarios known as Representative Concentration Pathways (RCPs), which include a “business-as-usual” scenario (RCP8.5) reflecting continued increases in greenhouse gas

emissions, and a climate change mitigation scenario, RCP4.5, which projects stabilization in overall radiative forcing by 2100(van Vuuren et al. 2011). The RCPs are named for the estimated radiative forcing measured in Watts per square meter (W/m²) in the year 2100 (e.g., 4.5 W/m² vs. 8.5 W/m²). RCPs offer projections of future climate under a set of pre-specified alternate potential realities; the actual trend will be determined by the choices that governments, corporations, and individuals worldwide make today and in the near future.

A number of studies have already provided important insights into the impact of continued climate change on future ozone-related health impacts. For instance, Post et al. used earlier-generation IPCC climate scenarios (Special Report on Emissions Scenarios A1 and A2) to compare ozone-related asthma ED visits in the United States in 2000 and 2050(Post et al. 2012). Other studies have focused on ozone-related asthma ED visits for a specific city, region, or other subnational spatial scale(Chang, Hao, and Sarnat 2014; Stewart et al. 2017; Johnson et al. 2017; Sheffield et al. 2011; Pannullo et al. 2017). On a global scale, Anenberg et al. described the present-day impacts of ozone on emergency department visits for asthma, reporting nine to twenty-three million ED visits worldwide and, in the Americas, estimating 3-6% of asthma ED visits as attributable to ozone today (Anenberg et al. 2018). Fann et al. projected ozone-related health impacts, estimating tens to thousands of deaths and illnesses, and the associated economic implications that could be expected in 2030 under RCP6.0 and RCP8.5(Fann et al. 2015). We extend this prior work by applying the most recent methods and data available to quantify the impact of continued climate change on ozone-related asthma ED visits locally and across the contiguous United States (CONUS). Specifically, our goal is to quantify the ozone-related health

benefits of climate change mitigation (represented by RCP4.5) versus “business-as-usual” (RCP8.5) in 2050.

2. Materials and methods

In order to quantify the potential health benefits of climate change mitigation, we used the health impact analytical program Benefits Mapping and Analysis Program – Community Edition (BenMAP – CE) (“Environmental Benefits Mapping and Analysis Program – Community Edition” 2014) to project the number of ozone-attributable asthma ED visits in 2045–2055 (referred to as “2050” for simplicity) under two alternate climate scenarios: RCP8.5 and RCP4.5. This approach applies the estimated present-day exposure response function between daily ozone levels and daily ED visits for asthma to alternate futures with different levels of daily ozone, assuming no changes in population characteristics or further adaptation. In secondary analyses, we also project the number of future asthma ED visits under projected population growth. Because the impact of ozone on asthma ED visits may vary across age groups, we project future health impacts for ages 0–4, ages 5–18, and all ages. BenMAP has been used extensively for similar health impact assessments (Garcia-Menendez et al. 2015; Kim et al. 2015; Sun et al. 2015; Broome et al. 2015; Johnson et al. 2017; Stewart et al. 2017; Berman et al. 2012; Tagaris et al. 2009; Bae and Park 2009; Grabow et al. 2012; Post et al. 2012; Fann et al. 2015).

2.1 Regional climate modeling and air quality monitoring

We projected daily maximum 8-hour (8-h) ozone levels from May–September for 2045–2055 under RCP4.5 and RCP8.5. The range of years is used to account for interannual variability in ozone projections. The ozone projections for the CONUS were generated using the Community

Multiscale Air Quality (CMAQ) model, version 5.2 (Appel et al. 2018). The meteorological conditions for CMAQ were derived from simulations of the Community Earth System Model (CESM)(Gent et al. 2011) following RCP4.5 and RCP8.5(Meehl et al. 2013). The CESM fields were dynamically downscaled to 36-kilometer grid cells over North America using the Weather Research and Forecasting (WRF) model version 3.4.1(Skamarock 2008), as previously described(Spero et al. 2016; Nolte et al. 2018). The anthropogenic emissions used for the CMAQ simulations were 2040 projections developed for analysis of the Environmental Protection Agency (EPA) Heavy-Duty Greenhouse Gas Rule("Emissions Inventory for Air Quality Modeling Technical Support Document: Heavy-Duty Vehicle Greenhouse Gas Phase 2 Final Rule" 2016), which represent substantial reductions relative to present-day emissions of nitrogen oxides (NO_x), sulfur dioxide, and volatile organic compounds (VOCs). Climate-sensitive VOCs emitted from vegetation, e.g., isoprene, were modeled within CMAQ using the downscaled meteorological projections from WRF (Spero et al. 2016; "Multi-Model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment" 2017; Nolte et al. 2018), but other categories of emissions that potentially could be affected by climate change (e.g., wildfires, electricity demand) were not.

2.2 Health impact estimation

The health impact function following Equation 1 was used to estimate the change in asthma ED visits on a county level under different ozone scenarios.

$$\Delta Y = Y_0 \cdot (1 - e^{-\beta \cdot \Delta O_3}) \cdot Pop \quad (1)$$

ΔY is the difference in the incidence of asthma ED visits attributed to the difference in ozone levels projected under RCP4.5 vs. RCP8.5, Y_0 is the baseline incidence rate (by age group) for asthma ED visits, ΔO_3 is the difference in ozone levels projected under the two RCPs on a 36-kilometer grid scale, Pop is the age-specific population (age 0–4, 5–18, and 0–99) on a county level, and β is the estimated slope of the relationship between daily ozone levels and asthma ED visits on the natural log scale. We used the exposure-response relationship between daily ozone and asthma ED visits reported in the meta-analysis by Ji et al. to generate the health impact function for all ages (**Supplemental Material, Table S1**)(Ji, Cohan, and Bell 2011). We used the study by Alhanti et al. to define the health impact function for children 0–4 and 5–18 years old (Alhanti et al. 2016). One of the strengths of the Alhanti et al. study is the multicity approach using ED visit and ozone data from three cities across the US.

Health impacts were calculated in BenMAP-CE under the two different climate scenarios for individual years 2045–2055 and then averaged within each scenario. Regional present-day incidence rates for asthma exacerbation ED visits are based on county-level ED visit data between 2011–2014 from the Healthcare Cost and Utilization Project and the Nationwide Emergency Department Sample, which are databases maintained by the Agency for Healthcare Research and Quality (Agency for Healthcare Research and Quality (AHRQ) 2009).

Population data were based on 2010 Census data in the analyses that held population constant (United States Census Bureau 2010). We used the Integrated Climate and Land-Use Scenario (ICLUS) population projections provided by the EPA to calculate health impacts when taking into account future population growth in 2050 ("Integrated Climate and Land-Use Scenarios

(ICLUS)"). In contrast to the conventional population projections commonly used, the ICLUS project was designed to account for changes in future climate when projecting population size and distribution.

2.3 Economic valuation

As in previous studies (Fann et al. 2015; Anenberg et al. 2017), the cost of future ED visits due to ozone-related asthma exacerbations was calculated following Smith et al. and Stanford et al., who evaluated the cost of ED visits due to asthma exacerbation in the US (Smith et al. 1997; Stanford, McLaughlin, and Okamoto 1999). We averaged the costs estimated by the Smith and Stanford studies using a 50% weight for each. We converted the cost, reported in 2010 US dollars (USD) by BenMAP, to 2018 dollars using the Consumer Price Index (CPI) for medical use (Bureau of Labor Statistics).

3. Results

3.1 Impact of climate change on ozone levels

Compared to “business-as-usual” (RCP8.5), following the climate change mitigation scenario (RCP4.5) would lead to lower ozone levels across most of the CONUS by 2050 (**Figure 1**).

Nationally, the population-weighted average daily maximum 8-h ozone levels for May–September are projected to be 1.86 parts per billion (ppb), or 4%, lower under RCP4.5 than in RCP8.5 in 2050, with substantial regional heterogeneity (**Supplemental Material, Figure S1**). The ten counties with the greatest difference in ozone concentrations under “business as usual” — ranging from 6.83 to 7.54 ppb more ozone relative to the mitigation scenario — are found in the interior of the CONUS, while some counties nearer the coasts (particularly in the states of

Maryland and Virginia in the mid-Atlantic region) have projected *decreases*, albeit of smaller magnitude, with differences ranging from 2.26 to 2.82 ppb *less ozone* under business as usual (**Supplemental Material, Table S2**). Under RCP4.5 vs. RCP8.5, the Los Angeles area and parts of the Midwest and Southwest are projected to have fewer days per year that exceed the US National Ambient Air Quality Standard for ozone of 70 ppb (United States Environmental Protection Agency 2015), with some areas seeing a decrease of 40 to 60 days per year during the ozone season (May–September) at 2050 (**Supplemental Material, Figure S2**).

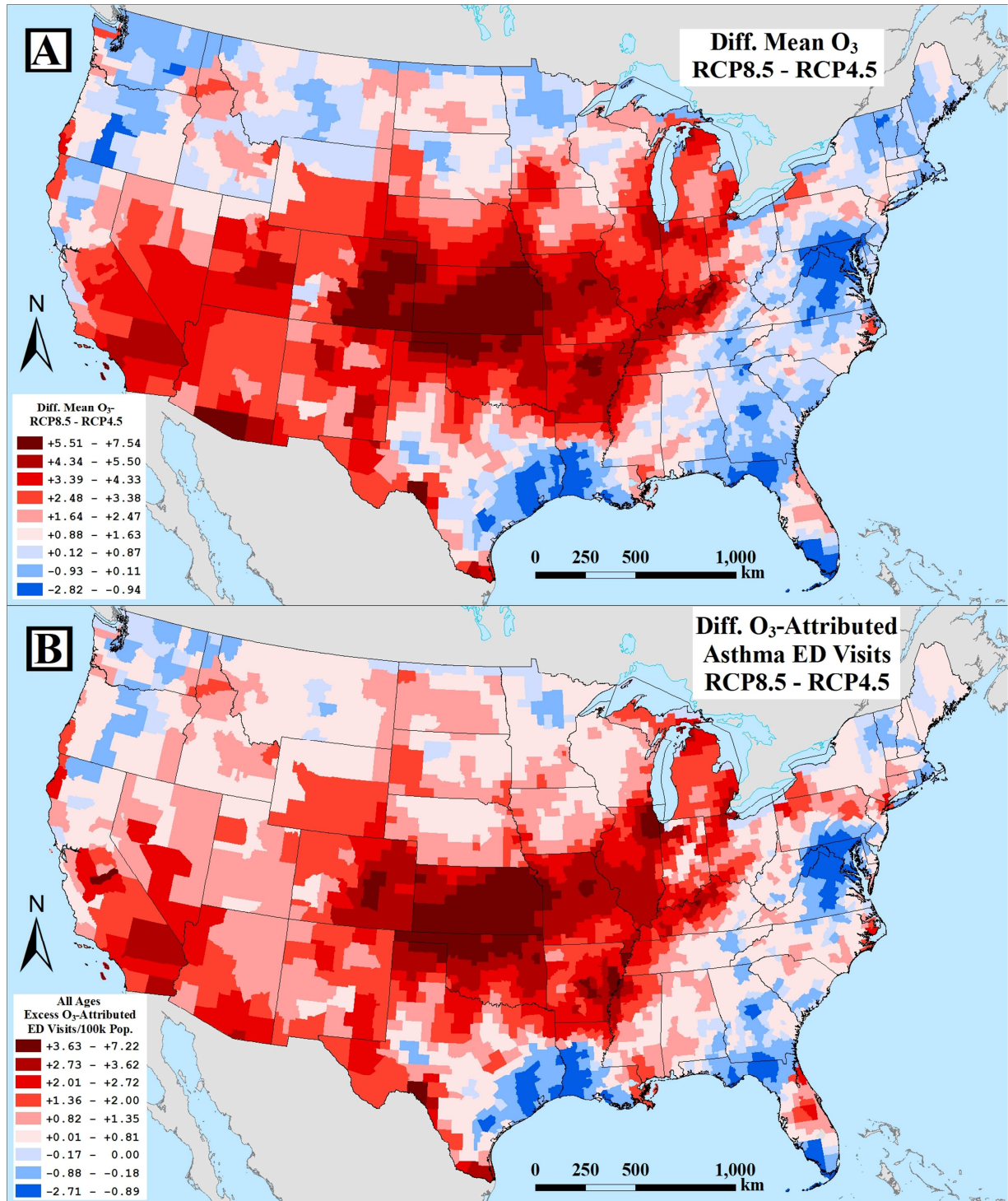


Figure 1. Panel A. The difference in estimated maximum daily 8-h ozone concentration under RCP8.5 compared to RCP4.5 in parts per billion (ppb) for May–September averaged over 2045–2055 on a U.S. county level grid. The red areas indicate lower average ozone levels under

RCP4.5 while the blue areas indicate higher ozone levels under RCP4.5. Panel B. Average annual number of averted ozone-related asthma ED visits per 100,000 people of all ages under RCP4.5 versus RCP8.5 for 2045–2055 on a county level for the United States. Positive (red) indicates fewer ozone-attributed ED visits with mitigation, while negative (blue) indicates more ED visits under RCP4.5 relative to RCP8.5. Abbreviations: Diff – difference; O3 – ozone; RCP – Representative Concentration Pathway; ED – emergency department

3.2 Impact of climate change on ozone-related asthma ED visits

The projected differences in ozone, which vary in their magnitudes depending on location, are associated with corresponding increases or decreases in estimated ozone-related ED visits (**Figure 1**). Under the “business-as-usual” scenario (RCP8.5), we estimate that there will be 84,000 ED visits due to ozone-related asthma exacerbations per year (during May–September) in the US in 2050. Following RCP4.5 and holding all other factors constant, we project that there would be 3,100 fewer ozone-related asthma exacerbation ED visits, on average, per year in 2050, as compared to RCP8.5. Expressed as a rate, this translates to a national average across the CONUS of 1.1 ED visit averted per 100,000 population under RCP4.5 vs. RCP8.5. The greatest benefits per 100,000 people would occur in parts of Oklahoma, Kansas, Texas, Arkansas, and California (**Figure 1**). Based on the geographic regions defined in the Third National Climate Assessment (**Supplemental Material, Figure S3**), the US Southwest and Midwest are projected to have the largest reductions in asthma exacerbation ED visit rates under RCP4.5 vs. RCP8.5 (**Table 1**). California has four of the top-ten counties with the highest absolute number of averted ED visits under RCP4.5, from 45 ED visits per year in Riverside County, California up to 247 in Los Angeles County, California. On the other hand, when expressed as a rate per 100,000

population, Arkansas has three of the top-ten counties with the largest reduction in ED visit rates, from 4.8 ED visits per 100,000 population in Dallas County, Arkansas up to 7.2 per 100,000 population in Phillips County, Arkansas (**Table 2**).

Table 1. Average absolute annual ozone-related asthma ED visits averted and average rate per 100,000 population based on 2010 census population data for all ages, for 0–4 years old, and for 5–18 years old, for 2045–2055 under RCP4.5 compared to RCP8.5 by National Climate Assessment (NCA) Region(Melillo, Richmond, and Yohe 2014)

NCA Region	Average O ₃ -related ED visits averted per year			Average yearly rate of O ₃ -related ED visits averted per 100,000 population		
	0–4 years old	5–18 years old	All ages	0–4 years old	5–18 years old	All Ages
Northeast	13	65	300	0.38	0.64	0.54
Southeast	16	86	370	0.37	0.67	0.54
Midwest	39	220	1000	1.2	2.2	2.0
Great Plains	19	96	410	0.69	1.3	1.1
Southwest	45	240	1000	1.2	2.2	1.8
Northwest	1	5	21	0.14	0.26	0.22
Total US	130	710	3100	0.72	1.3	1.1

Table 2. Top 10 counties with highest total number or highest rate per 100,000 population of averted ozone-related asthma ED visits for all ages under RCP4.5 compared to RCP8.5 for the CONUS for 2045–2055.

Counties with highest number of averted ozone-related ED visits (County, State)	Average O₃-related ED visits averted per year for all ages	Counties with highest rate of averted ozone-related ED visits (County, State)	Rate of O₃-related ED visits averted per year per 100,000
Los Angeles County, California	246.6	Phillips County, Arkansas	7.2
Maricopa County, Arizona	65.3	Jefferson County, Arkansas	6.1
Orange County, California	63.7	Madera County, California	6.1
San Bernardino, California	56.0	Ochiltree County, Texas	5.4
Queens County, NY	55.6	Seward County, Kansas	5.4
Wayne County Michigan	50.9	Texas County, Oklahoma	5.4
Cook County, Illinois	50.5	Stevens County, Kansas	5.1
Clark County, Nevada	48.4	Beaver County,	5.1

		Oklahoma	
Kings County, New York	47.3	Milwaukee County, Wisconsin	4.9
Riverside County, California	45.4	Dallas County, Arkansas	4.8

Based on differences in the concentration-response curves for different age groups, of which the all-ages group had the steepest concentration-response function (**Supplemental Material, Table S1**), the yearly rate of asthma ED visits under RCP4.5 vs. RCP8.5 shows that children ages 5–18 will benefit more when compared to all ages (**Table 1**). Our results show that an annual average of 710 ED visits for children 5 to 18 years old would be averted in 2050 under RCP4.5 vs. RCP8.5.

3.3 Economic valuation of ozone-related ED visits

The projected total annual cost of ozone-related asthma ED visits in 2050 under RCP8.5 is USD \$45 million. When taking population projections into account, California has five of the top-ten counties for avoided costs of ED visits due to ozone-related asthma exacerbations under RCP4.5 (**Supplemental Material, Table S3**). Across the CONUS, we project USD \$1.7 million in averted costs under RCP4.5, assuming no changes in population, and USD \$2.4 million in averted costs using the ICLUS population projections. Regionally, the Southwest and Midwest account for 65% of the total averted costs, or approximately USD \$1.6 million (in 2018 dollars), under RCP4.5 compared to RCP8.5 (**Supplemental Material, Table S4**).

4. Discussion

Continued climate change is expected to have pronounced adverse health impacts in every region of the US, as previously reviewed (USGCRP 2016). Our study adds to this extensive literature by projecting the impact of two different greenhouse gas scenarios on asthma ED visits in the near future. We provide both a broad evaluation of ozone-related asthma ED visits across the CONUS, as well as an evaluation at the county level. Ozone-related asthma exacerbation ED visits will vary geographically at 2050 under the “business-as-usual” and mitigation climate change scenarios. Our analysis quantifies a specific health benefit of mitigating climate change, which could lead not only to further reductions in ozone, but also to reduced ED visits for ozone-related asthma exacerbations.

While we project a modest difference in ozone-related asthma ED visits between two RCPs, providing a concrete illustration of the link between health and climate change mitigation helps lay the foundation for a broader understanding of these connections. Furthermore, our projections may underestimate future health benefits for multiple reasons. First, our analysis reflects only the impact of changed meteorological conditions on ozone and the related asthma effects, where the emissions of ozone precursors are held constant. Realistically, a mitigation pathway, as represented by RCP4.5, will necessitate a global reduction of emissions of anthropogenic ozone precursors. Lower ozone precursors result in lower ozone concentrations and consequently lower ozone-associated health effects, such as the acute asthma ED visits analyzed in this study, as well as potential chronic effects related to asthma development, lung development, and other respiratory disease risks due to ozone exposure. Second, the immediate

health co-benefits of additional initiatives to reduce ozone precursors beyond those included in the 2040 emissions projections used here would also reduce asthma exacerbations; immediate co-benefits are not quantified in this analysis. Third, our study describes only one of many pathways by which climate change mitigation would lead to health benefits in the short-term.

Prior studies have reported on endpoints similar to our study, including climate change-related future ozone levels, differences in future ozone-related health outcomes under different greenhouse gas emission scenarios, and economic impacts (Sun et al. 2015; Bell et al. 2007; Hogrefe et al. 2004; Chang, Hao, and Sarnat 2014; Tagaris et al. 2009; Fann et al. 2015; Dionisio et al. 2017; Garcia-Menendez et al. 2015; USGCRP 2016). However, direct comparison of our results to prior studies is difficult given differences in spatial scales, time periods, health outcomes, and age groups considered. Our results are consistent with the study by Fann et al. that showed heterogeneity across the CONUS in changes to mean daily 8-h maximum ozone levels between 1995–2005 and 2025–2035 under two different climate change scenarios (Fann et al. 2015). In contrast to prior studies, our study compares the health impacts of projected future ozone levels under two different RCPs – therefore allowing for an assessment of health benefits of future greenhouse gas emission reductions – while most prior studies have compared future health impacts to present day (Dionisio et al. 2017; Bell et al. 2007; Sun et al. 2015; Chang, Hao, and Sarnat 2014). Sun et al. compared daily maximum 8-h ozone levels between 2002–2004 and 2057–2059 and projected spatial differences in the US, with areas such as the Northwest experiencing an increase in ozone and the Southeast experiencing a decrease in ozone in the 2050s (Sun et al. 2015). Post et al. estimated differences in summertime ozone-related ED visits across three different regions of the US under older IPCC scenarios between 2000 and 2050

(Post et al. 2012). Depending on the climate model used, they projected a difference of hundreds to thousands of ED visits nationally under the different climate scenarios as compared to present day in a majority of the models applied (Post et al. 2012). Fann et al. projected USD \$500,000 (in 2010 dollars) in additional annual costs due to ozone-related respiratory emergency department visits for all ages in 2030 under RCP8.5 as compared to the year 2000 (Fann et al. 2015).

4.1 Heterogenous ED visit distribution

Across the CONUS, our study highlights the heterogeneity of ozone-related ED visits across both NCA regions and counties. Based on geographic differences in projected ozone concentrations under RCP4.5 vs. RCP8.5, as well as differences in the baseline incidence of asthma, the distribution of ozone-related ED visits will vary. Regionally, the Southwest and Midwest are projected to benefit the most in avoided ED visits under RCP4.5. At the county level, the largest absolute differences in ozone-related asthma ED visits under RCP4.5 are projected for counties that include the cities of Los Angeles, Las Vegas, Phoenix, New York City, Detroit, and Chicago. However, while multiple populous counties, particularly in California, appear to benefit disproportionately in terms of absolute number of ED visits avoided under RCP4.5 as compared to RCP8.5, the Great Plains region contains five of the top ten counties in avoided ED visits per 100,000 population under RCP4.5.

Our results also show that a small number of places in the U.S. may see slightly higher ozone concentrations and, consequently, asthma exacerbation ED visits under RCP4.5. Understanding

the geophysical drivers of these increases requires further investigation. But overall, our results show a net ozone and health benefit of mitigating climate change (i.e. RCP4.5 vs. RCP8.5).

4.2 Age distribution

Within the heterogeneous distribution of ozone-related ED visits for asthma, there is a difference in how various ages are projected to be impacted under the two RCPs. Under RCP4.5, children 5–18 years old would experience the greatest reduction in rate of ozone-related asthma ED visits as compared to 0–4 years old and people of all ages. Diagnosing asthma exacerbations in children less than 5 years old is difficult and can limit the classification of asthma ED visits in children in this age group (Potter 2010), likely underestimating the true baseline rate of ED visits for asthma. Studies have hypothesized that the greater susceptibility to ozone observed among children is at least partly due to children typically spending more time outdoors during peak ozone times and the increased amount of air they breathe (measured as minute ventilation) compared to adults who have lower minute ventilation and are often indoors during peak ozone hours (Mar and Koenig 2009; Sheffield et al. 2011). Indeed, prior studies consistently show that the association between asthma and ozone concentration is weaker among the elderly compared to younger adults and children (Zu et al. 2017; Alhanti et al. 2016; Silverman and Ito 2010; Strosnider et al. 2019). Also specifically relevant to this younger population are the possibility of chronic effects of ozone-exposure as ozone potentially plays a role in asthma development (affecting the baseline prevalence of the disease) and also impaired lung development in children, which can contribute to life-long consequences in terms of predisposition to other respiratory disease apart from asthma (United States Environmental Protection Agency 2019). Thus, the health burden estimates here are inherently conservative.

4.3 Economic impact

While the projected cost savings under RCP4.5 vs. RCP8.5 are modest compared with the overall USD \$56 billion cost of asthma in the US annually, the costs or potential cost savings are not expected to be evenly distributed across the US (Wang et al. 2014). When also considering population growth, the greatest savings are projected for Los Angeles County, California. These costs are likely underestimated as the economic valuation is based on two older studies that report an estimated average cost of an ED visit for asthma exacerbation of USD \$483 and USD \$666 (in 2018 dollars)(Smith et al. 1997; Stanford, McLaughlin, and Okamoto 1999). A more recent study suggested the cost of an ED visit for asthma exacerbation may be closer to USD \$2000 (in 2018 dollars) (Wang et al. 2014). This implies that our valuation could be underestimated by a factor of nearly 3.5. Using these newer ED cost estimates by Wang et al., the total cost of ozone-related ED visits in 2050 will be USD \$156 million under RCP8.5 and the averted costs by adhering to RCP4.5 vs. 8.5 will be USD \$8.35 million accounting for population growth. ED visit cost is not the primary outcome of interest in this study, however the combined effects of the cost of ED visits with lost work and school days or lost productivity, and increased medication use (none of which are included in these cost estimates) demonstrate that the associated morbidity and mortality from asthma exacerbations could place a heavy economic burden on the health care system.

4.4 Limitations

There are multiple limitations and sources of uncertainty in our study. The first is in projecting daily maximum 8-h ozone, which is subject to uncertainties in the CESM, WRF, and CMAQ

models. We attempted to limit the impact of interannual variability for ozone emissions by averaging the simulated years 2045–2055 to offer a representative estimate of mid-century ozone concentrations. While we cannot categorically exclude the potential for interdecadal modes of climatic variability to influence the absolute magnitude of our results, we assumed that this contribution was small relative to the anthropogenic warming effects in the RCP scenarios. Second, ozone formation depends on precursor emissions that may be affected by climate change in ways that were not incorporated into our air quality modeling. For example, more frequent wildfires and higher temperatures may increase precursor emissions and result in more ozone-related asthma exacerbations than we project (Fann et al. 2015). Future studies should consider the impacts of climate change on particulate matter concentrations as well as ozone to better characterize the overall health impacts of climate change. Third, these projections do not include Alaska, Hawaii, and U.S. territories, such as Puerto Rico (with a population of three million and a high baseline asthma prevalence rate), also likely leading to an underestimate of the projected impacts nationwide. Unless otherwise specified, we held population constant for most of our projections. However, population changes will alter the number of ED visits and the distribution of those ED visits both geographically and according to the different age groups. We report crude rates rather than age-adjusted rates, which take into account differences in event rates by age groups. Our projections also assume a constant exposure-response function based on an epidemiologically determined asthma rate for a given ozone level increase, which could increase or decrease in the future depending on changes in asthma control medications, healthcare access, other medical management changes, as well as shifts in underlying susceptibility of the population. Lastly, another limitation of this analysis (and indeed any analysis that values future air quality impacts using cost of illness measures) is that the monetary unit values do not account

for future changes in the cost of healthcare. The assumptions and limitations of our study are consistent with similar previously published studies (Alexeeff, Pfister, and Nychka 2016; Fann et al. 2015; Garcia-Menendez et al. 2015; Post et al. 2012).

4.5 Strengths

On the other hand, our study has multiple strengths. For one, we provide an assessment of future ozone-related asthma exacerbation ED visits across the CONUS on a spatial scale that highlights the geographic heterogeneity of the health impacts of ozone and of global climate change mitigation. To project how asthma will be affected in the future as a result of climate change, we extend previous epidemiologic studies that have studied the effects of present-day ozone levels on asthma ED visits and use a meta-analysis to define the concentration response function (Ji, Cohan, and Bell 2011; Zheng et al. 2015; Tagaris et al. 2009; Berman et al. 2012). Additional strengths are the use of two of the most recent IPCC climate scenarios, RCP4.5 and RCP8.5, while similar studies used the prior generation of IPCC climate scenarios (Post et al. 2012), and the inclusion of the economic valuation. Finally, by comparing two RCPs in the future, our analysis enabled an assessment of one potential health benefit of climate change mitigation, specifically asthma exacerbations.

5. Conclusions

Under the “business-as-usual” RCP8.5 climate scenario, mid-century ozone concentrations are projected to contribute to an estimated 84,000 asthma ED visits per year with annual costs between USD \$45 million and \$156 million. By contrast, adhering to the RCP4.5 mitigation scenario would lead to fewer ozone-related ED visits and a concomitant reduction in healthcare

costs compared to RCP8.5, on average across the CONUS. Our study projects that the benefits of mitigation are not uniformly distributed across the country with the Southwest and Midwest projected to see the largest health benefits. This information can inform policy makers working to mitigate the effects of climate change and protect human health.

Supplementary material: The following supplemental tables and figures are available: Figure S1. Mean O₃ concentrations during May-September 2045-2055 for the CONUS under RCP8.5 and under RCP4.5; Figure S2. Difference in number of days with ozone exceeding 70 ppb between RCP4.5 and RCP8.5; Figure S3. NCA regions; Figure S4. Averted ozone-related ED visits for children 0–4 years old; Figure S5. Averted ozone-related ED visits for children 5–18 years old; Figure S6. Averted ozone-related ED visits for all ages assuming constant population and for all ages integrating ICLUS population projections for 2050; Table S1. Effect estimates for ozone-related health impacts; Table S2. Top ten counties with greatest differences in ozone under RCP8.5 compared to RCP4.5 across the CONUS; Table S3. Top ten counties with highest cost savings under RCP4.5 compared to RCP8.5 using ICLUS 2050 population projections; Table S4. Cost savings under RCP4.5 versus RCP8.5 by NCA Region using ICLUS 2050 population projections. Ozone data used for this study will be available through the U.S. government portal at data.gov.

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Conflicts of Interest: Dr. Wellenius has served as a paid member of multiple expert panels for the Health Effects Institute (Boston, MA) providing expertise on the health effects of ambient air pollution. Dr. Wellenius currently serves as a paid visiting scientist at Google.

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Highlights

- We estimate tens to thousands of ozone-related asthma ED visits per year in 2050
- There is significant heterogeneity in the geographic distribution of ED visits
- In the mitigation scenario, fewer ozone-related ED visits are projected nationally
- The annual averted costs are projected to be in the millions of dollars

Declaration of interests

☐ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Dr. Wellenius has served as a paid member of multiple expert panels for the Health Effects Institute (Boston, MA) providing expertise on the health effects of ambient air pollution. Dr. Wellenius currently serves as a paid visiting scientist at Google.