

Climate Change will Increase Ozone Levels and unravel Air Quality Regulations

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Title: Climate Change will Increase Ozone Levels and Unravel Air Quality Regulations

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Abstract: Using daily data for the United States over the period 1980-2019, we estimate the impacts of temperature on ambient ozone concentrations, accounting for adaptation to climatic change. We find that even with adaptation, rises in temperature will steeply increase ozone levels by over 9 ppb on days above 25°C. By mid-century, we calculate that 189 additional counties will be violating the air quality standards, with 33 million more residents exposed to unhealthy levels of ozone. Climate change will thus likely increase the costs of compliance with existing ambient ozone standards. In light of a recent EPA ruling that would effectively remove co-benefits of ozone precursor reductions from the cost-benefit analysis of those standards, they will be in peril, further threatening public health.

Main Text:

It is well established that ambient ozone causes detrimental health effects, leading to mortality and morbidity (1–2). Estimates of the global burden of disease indicate that 9-23 million annual asthma emergency room visits globally in 2015 could be attributable to ozone, representing 8-20% of the annual number of visits (3). Ozone affects both the young and the old, even at levels below the current U.S. Environmental Protection Agency’s (EPA) National Ambient Air Quality Standards (NAAQS) (4). Yet, progress on reducing the levels of ozone relative to other criteria pollutants has been limited over the last forty years (5), and a deeply flawed EPA ruling at the end of the Trump Administration has threatened the grounds for the current level of regulatory oversight on ozone (6). The rule, which remains in effect, disregards indirect co-benefits of the ozone NAAQS in the form of improved public health associated with the concomitant reduction of other air pollutants. Because ozone standards rely on indirect benefits from reductions in particulate matter concentrations to comfortably pass a cost-benefit analysis, they are in jeopardy for the next revision in a few years (7).

Climate change may further put the ozone standards at risk if rising temperatures increase ozone concentrations, and ultimately the costs of compliance with these standards. There is a growing recognition that climate change will affect ozone levels. Indeed, there is a literature on the so-called *climate penalty* on ozone – that is, the impact of climatic changes on ozone – indicating that this penalty can be substantial (8, 9). But important knowledge gaps remain. First, it is still not clear exactly how much climate change will increase ozone concentrations because there can be adaptation to climate change, and the ozone NAAQS themselves may act as catalysts for such adaptation (10). If a county violates the standard because average temperature has risen – not because ozone precursor emissions of NO_x and VOCs have risen – individuals and firms may

still be forced to curb emissions of ozone precursors in order to comply with air quality regulations. These adjustments may preclude excessive increases in ozone levels even under climatic changes, but may come with associated increases in compliance costs. Second, ozone may respond differently to higher temperatures across regions. Places that have experienced extreme temperatures relatively often may have already made key adjustments. Therefore, adaptation might manifest differently in regions that experience varying baseline climates.

In this study, we build on an econometric method we recently developed (11) to estimate the impact of long-run (climatic) temperature changes on ozone in the United States. Our approach has two main elements: The first is the decomposition of meteorological variables into long-run climate normals and short-run weather shocks. The second is the ability to identify responses to weather shocks and climatic changes in the same estimating equation. Individuals and firms respond to information on climatic variation they have observed and processed over the years. In contrast, they may be constrained in their response to short-term, unanticipated weather shocks. Our measure of adaptation is the difference between those two responses by the same economic agents. We combine daily ozone data from the EPA with daily weather data from the National Oceanic and Atmospheric Administration (NOAA) for the period 1980-2019 (Figs. S2 – S5 & SI section S2). Splitting temperature into 5°C bins (Figs. S8 – S7), we estimate the differential relationship between climate normal temperature and ozone across the temperature distribution nationally and for each of the nine NOAA climate regions (Tables S1, S2 & SI section S4). We then predict ozone levels by mid-century, relying on climate change projections (12). Ultimately, we are able to project how many more counties would violate the NAAQS for ozone by mid-century, in the absence of further action to control ozone concentrations. Finally, we assess the consequences of climate change to the cost-benefit analysis of ozone standards, and suggest that

– in the absence of co-benefits – climate change will unravel ozone standards and, as a result, may further threaten public health. We highlight three main findings.

The relationship between temperature and ozone resembles a *reclining beach chair*, with steep increases in ozone of over 9 ppb on days above 25°C (Fig. 1). The relationship between temperature and ozone is relatively flat until the 20-25°C temperature bin, but the slope becomes steep at 25-30°C and beyond. Indeed, even though adaptation reduces the effect of temperature on ozone by approximately 40% (Table S3), ozone concentrations still increase substantially by over 9 and 15 ppb when temperatures are 25-30°C or above 30°C, respectively, relative to 15-20°C. Furthermore, under the business-as-usual greenhouse gas emissions scenario embedded in the Representative Concentration Pathway (RCP) 8.5, average U.S. temperatures will increase by 1.6°C by mid-century (12), implying a significant right-ward shift in the distribution of temperature days with more than double the number of days above 30°C during the ozone season by mid-century.

The relationship between temperature and ozone exhibits substantial heterogeneity among the nine U.S. climate regions (Fig. 2). The relationship between temperature and ozone is steepest for regions which have higher levels of baseline ozone, such as the Northeast and Ohio Valley (Table S4). In contrast, regions with lower average ozone concentrations (Northwest, Rockies) or those that have consistently faced hot temperatures (South, Southwest) have a flatter relationship, or a significantly reclined beach chair. However, climate projections indicate these warmer regions will have substantial increases in the number of days above 30°C by mid-century. All regions are projected to see an increase in the number of days between 25-30°C or above 30°C by mid-century.

Under current ozone abatement levels, 189 additional counties will be violating ozone standards by mid-century, with 33 million more residents exposed to unhealthy levels of ozone (Fig 3A).

Since the 1980's the share of monitored counties in violation of the ozone standards has been steadily declining. Of the 346 counties continuously monitored throughout the period 2016-2019, one hundred were designated as in violation of the ozone standards, accounting for 66.8 million U.S. residents – approximately 20% of the U.S. population by the 2018 American Community Survey's 5-year estimates. However, an additional 189 of these counties are projected to be in violation of the ozone standards by mid-century. By current population counts, this would subject 33 million more individuals to unhealthy levels of ozone – extending harmful exposure to approximately 31% of the U.S. population. Historical and projected violations of the ozone standard in each climate region generally follow the same deep “V”-shaped national trend in county violations (Fig. 3B), with a few exceptions associated with the more muted response by some climate regions as described above (Fig. 3C). Projected changes in ozone standard violations under the RCP 4.5 climate scenario are qualitatively similar (Fig. S10).

Our results imply that increases in ozone concentrations due to increases in average temperature would lead many additional counties to become out of attainment – unless they step up pollution abatement efforts to reduce ozone levels. Climate projections under business-as-usual emissions scenarios imply that ozone concentrations in July – typically the worst month of the year for ozone – would increase by 4 ppb by mid-century (Table S5). To put this climate-induced increase in ozone levels into perspective, EPA's last change of the ozone standards in 2015 decreased the threshold from 75 to 70 ppb. Thus, 80% of that 5-ppb decrease would be undone by mid-century, on average. In essence, for counties to remain in attainment with the current 70 ppb standards, it would be as if they had to meet a standard of at least 66 ppb. Such reductions

will be costly. By EPA's calculations in their 2015 regulatory impact analysis (13), reducing the ozone standards to 65 ppb would incur an additional \$14.6 billion (2011 dollars) per year due to increased compliance costs in 64 counties. In order to keep the 189 additional counties projected to go out of attainment by mid-century below the 70 ppb standard, annual compliance costs
5 could increase by up to \$43.6 billion based on current technology (Table S6 & SI section S5).

A similar back-of-the-envelope calculation of the benefits from achieving compliance with a 70 ppb standard for these counties using the same EPA analysis indicates an average annual benefit of \$59.1 billion (Table S7). Comparing these costs and benefits would suggest that the ozone standards be retained. However, about two-thirds of the total benefits under the current ozone
10 standards are derived from co-benefits due to concomitant reductions in particular matter. The recent 2020 EPA ruling based on deeply flawed analysis (6) would exclude such co-benefits from future benefit-cost analyses of ozone and other pollution standards – despite analysis showing that as long as co-benefits are carefully estimated, they should indeed count as much as direct benefits (14).

15 Excluding co-benefits, the back-of-the envelope benefits would fall below the compliance costs at just under \$20 billion. Thus, the combination of rising compliance costs due to climate change, and the artificial reduction in calculated benefits due to this ruling, threatens to unravel ozone regulations and compromise public health in the United States.

Methods

A body of literature in environmental economics and related fields has attempted to quantify the economic impacts of climate change (15). Earlier methods to estimate the impact of climate change on economic outcomes have either used cross-sectional approaches that rely on permanent meteorological conditions (16, 17) or panel fixed-effects approaches that exploit unanticipated weather shocks (18, 19). We developed a unifying approach that has two key elements: First, a decomposition of meteorological variables. Second, the ability to recover estimates of both the short- and long-run impacts of climate change in the same equation. Taking the results of this model, we then apply climate projections from the RCP 4.5 and 8.5 scenarios to predict Ozone levels and county violations of the standards by mid-century (SI section 3).

Decomposition of meteorological variables: norms vs. shocks — daily temperature is decomposed into its long-run component, and its short-run deviation from this value:

$$Temp = Temp^C + Temp^W, \quad (1)$$

where $Temp^C$ represents climate normal temperature, and $Temp^W (\equiv Temp - Temp^C)$ deviations from the norm. We focus on temperature around the location of ozone monitor i in day t of month m and year y , and construct 5°C temperature bins before decomposing each bin into $Temp^C$ and $Temp^W$ by defining $Temp^C$ as the 30-year monthly moving average (MA) of past temperatures. We then average each bin by month – in essence, these monthly averages now reflect the “share” of the month in which the daily temperature fell within the respective bin. Next, we create the 30-year monthly MA – “climate norms” – by taking the 30-year average of these monitor-level monthly averages for each bin.

Econometric Model — The econometric specification is:

$$\begin{aligned} Ozone_{it} = & \beta_{15}^C(Temp_{it}^C < 15) + \beta_{20}^C(20 \leq Temp_{it}^C < 25) \\ & + \beta_{25}^C(25 \leq Temp_{it}^C < 30) + \beta_{30}^C(Temp_{it}^C \geq 30) \\ & + X_{it}\delta + \phi_{isy} + \epsilon_{it} \end{aligned}$$

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(2)

where i represents an ozone monitor, t denotes day, s season (Spring or Summer) and y year. As previously mentioned, our analysis focuses on the most common ozone season in the U.S. – April to September – in the period 1980-2019. The dependent variable *Ozone* captures daily maximum ambient ozone concentration. $Temp^C$ represents the climate norm component of daily temperature. The only functional form restriction is that the impact of temperature on ozone is constant within 5°C intervals. The matrix of additional control covariates X contains daily temperature shocks ($Temp^W$) and a similar decomposition of precipitation norms and shocks; while ϕ reflects *monitor-by-season-by-year* fixed effects, and ϵ an idiosyncratic term. In all estimations standard errors are clustered at the county level.

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When predicting Ozone levels by mid-century, the analysis holds constant a number of factors that might amplify the impacts of climate change on ozone concentrations. Climate change will likely trigger other events, such as forest fires, that may exacerbate ozone formation by further increasing ozone precursors. It might also increase the length or geographic breadth of the current ozone season (20), potentially adding months of exposure to unhealthy levels of ozone.

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For these reasons, our results should be seen as a lower bound of the impacts of climate change on ozone. Therefore, retaining the ozone standards in this changing climate is even more crucial.

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Data and materials availability: Data on ambient ozone concentrations, as well as the weather data and climate projections, are all freely accessible online (see supplementary materials for links). Data and code used in our analysis are available at:

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<https://doi.org/10.5281/zenodo.4759889>

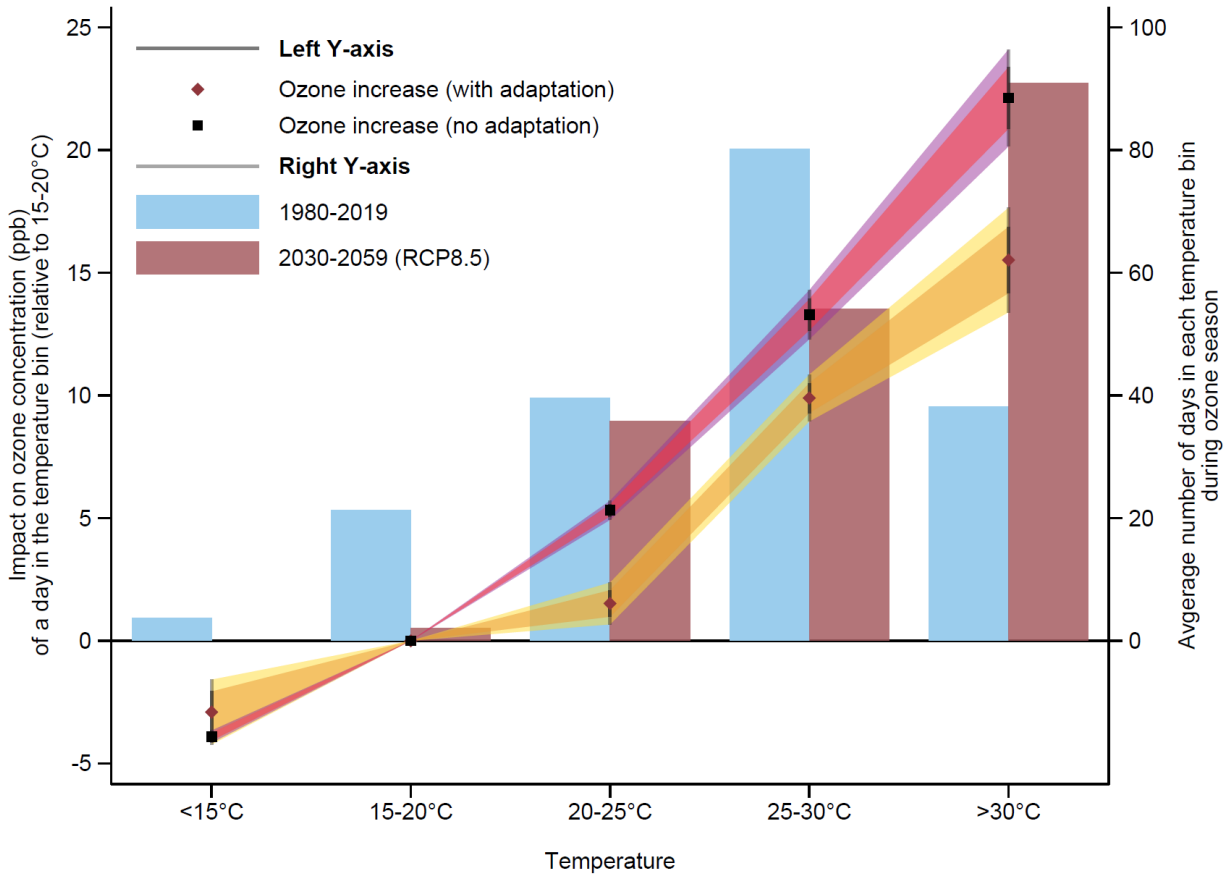


Fig. 1. Climate change & the steep effects of temperature increases on ozone

concentrations. Blue (historical) and red (projected, RCP 8.5) histograms depict the average number of days that maximum temperature was – or is projected to be – within each temperature bin during the ozone season, corresponding to the right y-axis. The x-axis denotes five temperature bins: below 15°C, 15-20°C, 20-25°C, 25-30°C, and above 30°C. The left y-axis indicates the average change in daily maximum ozone concentration, in parts per billion (ppb), for each temperature bin, relative to the 15-20°C reference point. The red diamond and black square symbols depict the estimated effect on ozone for each bin, with and without adaptation respectively, while the shaded areas denote the corresponding 90% and 99% confidence intervals. Corresponding point estimates and standard errors are reported in Table S1.

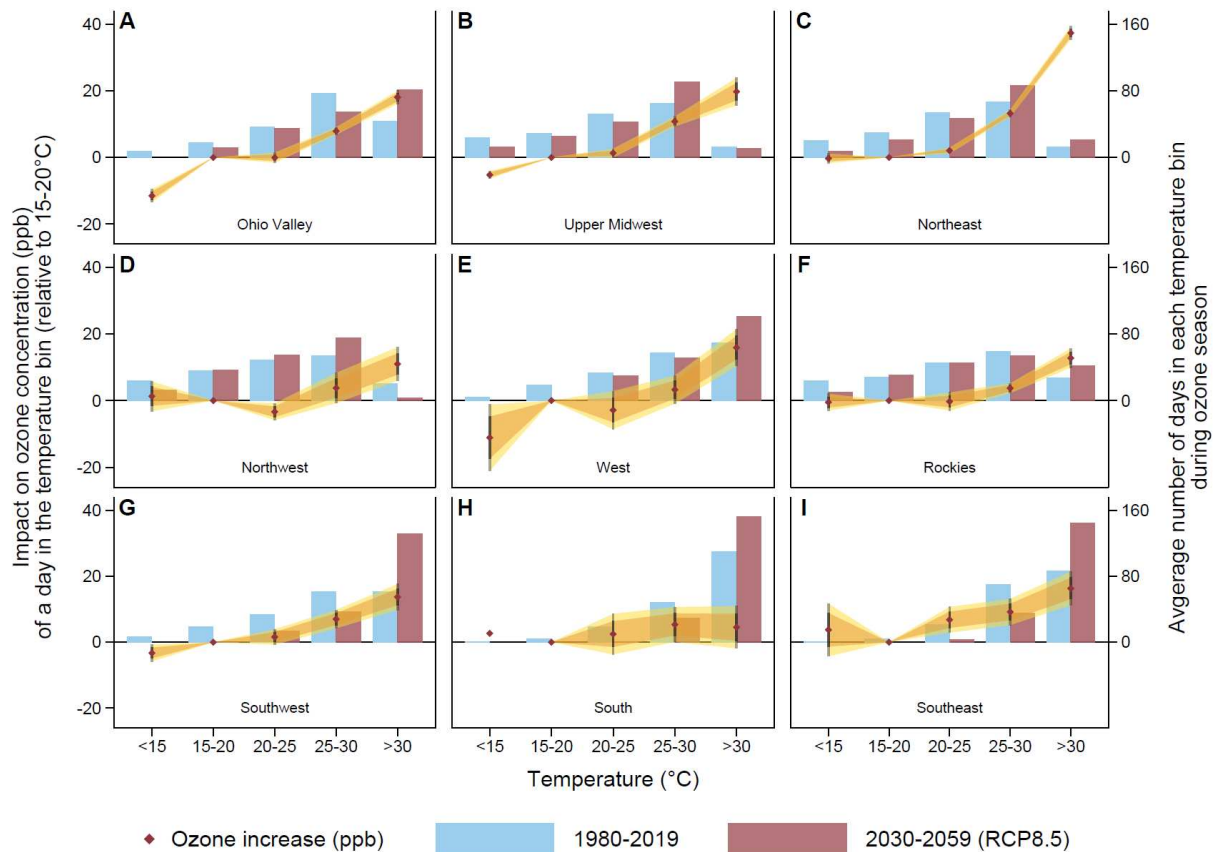


Fig. 2. Regional differences in climate change & the effects of temperature increases on

ozone concentrations. We disaggregate the national histograms and estimated temperature-

ozone relationship illustrated in Fig. 1 by climate region. Corresponding point estimates and

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standard errors are reported in Table S2. (A) Ohio Valley, (B) Upper Midwest, and (C) Northeast

make up the three northern climate regions. (D) Northwest, (E) West, and (F) Rockies make up

the three western climate regions. (G) Southwest, (H) South, and (I) Southeast make up the three

southern climate regions. There is distinct heterogeneity in both the historical and projected

climate distributions and in the temperature-ozone relationship across the nine climate regions,

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indicating that some regions may face more severe effects of climate change on ozone

concentrations than others.

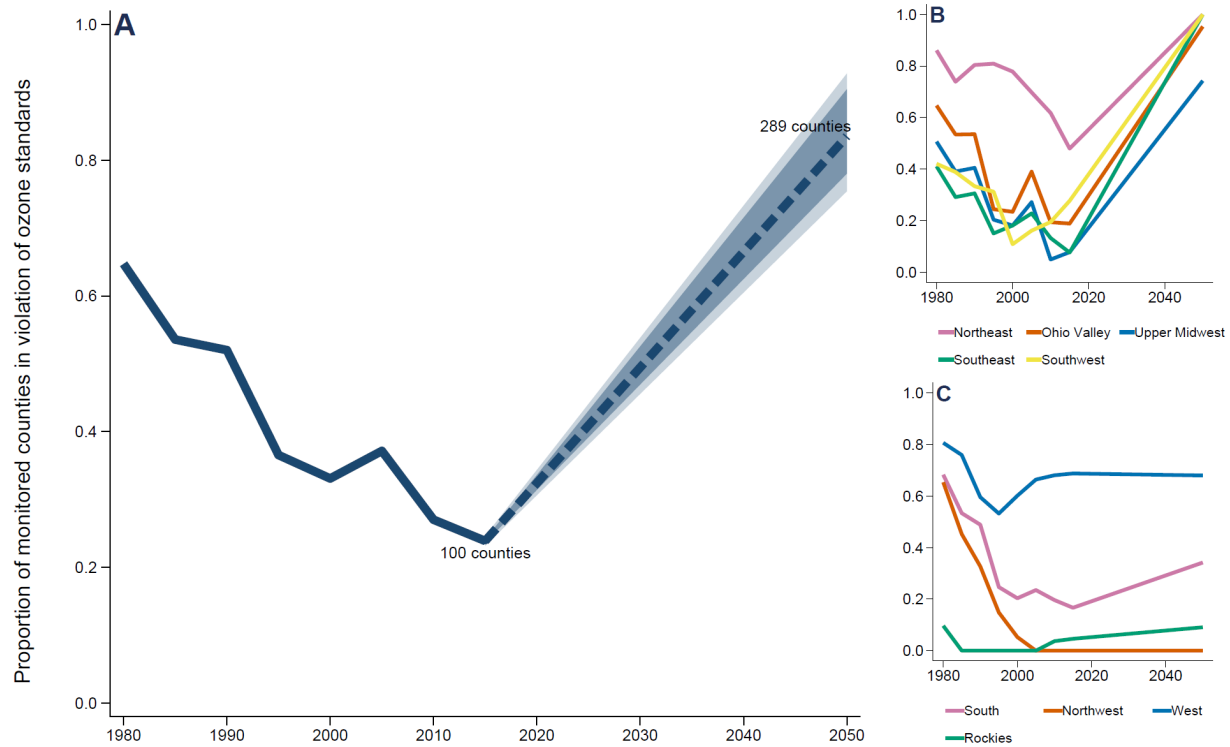


Fig. 3. Climate change will increase county violations of the ozone standards. Nationally

(A), the proportion of monitored counties in violation has been declining since 1980 and is

currently just under 25%. Holding constant current ozone control activities, approximately 84%

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of currently monitored counties will be in violation of the standards by mid-century – higher than

when the EPA first began regulating ozone directly. Shaded areas depict the 90 and 99%

confidence intervals based on econometric model estimates. (B) illustrates the historical and

projected trends in county violations for the five climate regions that follow a similar “V”-shaped

trend. (C) does so for the four climate regions with flatter projections.

Supplementary Files

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