Environmental and Resource Economics (2023) 86:305–343
https://doi.org/10.1007/s10640-023-00793-3

Incidental Adaptation: The Role of Non-climate Regulations

Antonio M. Bento[1,2] · **Noah Miller**[1] · **Mehreen Mookerjee**[3] · **Edson Severnini**[4,2,5]

Accepted: 28 June 2023

Abstract

When a non-climate institution, policy, or regulation corrects a pre-existing market failure that would be exacerbated by climate change, it may also incidentally induce climate adaptation. This *regulation-induced adaptation* can have large positive welfare effects. We develop a tractable analytical framework of a corrective regulation where the market failure interacts with climate, highlighting the mechanism of regulation-induced adaptation: reductions in the climate-exacerbated effects of pre-existing market failures. We demonstrate this empirically for the US from 1980 to 2013, showing that ambient ozone concentrations increase with rising temperatures, but that such increase is attenuated in counties that are out of attainment with the Clean Air Act's ozone standards. Adaptation in nonattainment counties reduced the impact of a 1 °C increase in climate normal temperature on ozone concentration by 0.64 parts per billion, or about one-third of the total impact. Over half of that effect was induced by the standard, implying a regulation-induced welfare benefit of \$412–471 million per year by mid-century under current warming projections.

Keywords Climate change · Government regulations and policy · Clean Air Act · Regulation-induced adaptation · Ambient ozone concentration

JEL Classification Q53 · Q54 · Q58 · H23 · K32 · P48 · D02

We thank Max Auffhammer, Karen Clay, Michael Greenstone, Amir Jina, Andrea La Nauze, Margarita Portnykh, Lowell Taylor, and seminar participants at Carnegie Mellon, Columbia, Insper-Sao Paulo, Penn State, UC-Davis, UCLA, UCSD, University of Chicago—EPIC, AERE Summer Conference, SEEPAC Research Workshop: Advances in Estimating Economic Effects from Climate Change Using Weather Observations (SIEPR—Stanford University), International Workshop on Empirical Methods in Energy Economics, and the Northeast Workshop on Energy Policy and Environmental Economics, for invaluable comments and suggestions. The authors gratefully acknowledge financial support from the Berkman fund, Heinz College, and Wilton E. Scott Institute for Energy Innovation at Carnegie Mellon University.

Extended author information available on the last page of the article

1 Introduction

Many government institutions, policies, and regulations have been established to help smooth out private shocks in varied contexts such as employment, health, or housing.[1] Due to the nature of climate change, however, some of these shocks are likely to become more frequent and/or severe (IPCC 2021), and it is unclear, a priori, whether these existing institutions, policies, and regulations may induce or constrain private climate adaptation.[2] On the one hand, existing government policies may distort private decisions, inhibiting agents' adaptation; on the other hand, they may correct market failures, inducing adaptation. Given the political gridlock surrounding climate change mitigation efforts, understanding whether existing policies can induce climate adaptation is of particular importance (Nordhaus 2019; Aldy and Zeckhauser 2020; Goulder 2020), though notably such policies should be viewed as complements, rather than substitutes, of first-best climate policy.[3] This study conceptualizes and demonstrates the possibility for *regulation-induced adaptation*, examining the context of the existing National Ambient Air Quality Standards (NAAQS) for ozone pollution.[4]

We develop a tractable analytical framework to highlight how pre-existing regulatory incentives can affect behavioral responses to climate change and thus may incidentally induce or inhibit climate adaptation. We then econometrically recover key parameters to calculate the welfare effects of the regulation-induced adaptation co-benefit of the ozone NAAQS. An advantage of our econometric approach is that it recovers a measure of adaptation arising from the behavior of the *same* economic agents. This allows us to compare the relative magnitudes of adaptation between counties in or out of attainment with the NAAQS regulation, in the *same* estimating equation, to empirically recover a measure of regulation-induced adaptation without making further assumptions over preferences across time or place.

We estimate adaptation in both attainment and nonattainment counties as the difference between the ozone response to increases in temperature due to transitory weather shocks and shifts in the climate normal temperature. Weather shocks, by their nature, are observed

---

[1] For example, unemployment insurance helps households smooth out the income effects of a labor shock, leading to more efficient labor outcomes (Acemoglu and Shimer 1999) and helping to avoid home foreclosures (Hsu et al. 2018). Similarly, medical insurance—whether directly provided via Medicare/Medicaid, or facilitated through, e.g., a local Affordable Care Act health exchange—can smooth out negative health shocks by increasing access to care (e.g., Doyle Jr 2015), while the National Flood Insurance Program covers over a trillion dollars' worth of housing and related assets (Michel-Kerjan 2010).

[2] The IPCC defines adaptation as "the process of adjustment to actual or expected climate and its effects in order to moderate harm or take advantage of beneficial opportunities," and further states that "[a]daptation plays a key role in reducing exposure and vulnerability to climate change. (...) In human systems, adaptation can be anticipatory or reactive, as well as incremental and/or transformational." (IPCC 2022).

[3] Furthermore, although market forces can lead to adaptation, that alone may not be enough to adequately adapt to climatic changes and may lead to devastating distributional impacts.

[4] Ozone is a local pollution externality formed by a production function that exhibits Leontief-like properties in its inputs (Auffhammer and Kellogg 2011)—"precursor" emissions of Nitrogen Oxides (NOx) and Volatile Organic Compounds (VOCs)—in the presence of sunlight and warm temperatures; hence, affected by climate change. Exposure to ambient ozone has important economic implications because it leads to increases in hospitalization, medication expenditure, and mortality (e.g., Neidell 2009; Moretti and Neidell 2011; Deschenes et al. 2017). Beginning in 1980, the Environmental Protection Agency (EPA) has monitored and regulated ambient ozone concentrations via the ozone NAAQS to protect human health. The NAAQS themselves set a pollution concentration threshold that counties cannot exceed, reducing the frequency and magnitude with which individuals face pollution exposure shocks.

simultaneously with their impact on ozone concentrations, affecting ozone formation directly—conditional on the level of ozone precursor emissions—such that agents have few if any avenues to adjust their behavior in response to weather shocks. On the other hand, shifts in the expected climate norm are observable by agents by, for example, looking at the average temperature of previous years, and thus may affect the level of precursor emissions if agents adapt to a shifting climate by changing their emissions profile. Therefore, while an increase in temperature would typically increase ozone concentrations, counties in violation of the ozone air quality standard—those designated as out of attainment, or in "nonattainment" with the NAAQS—would be pressured to take action to bring those levels down, adapting to expected climate normal temperatures and thus attenuating the climate impact. In other words, climate adaptation induced by the NAAQS. We account for any "baseline" level of adaptation or other confounding effects by differencing out the measure of adaptation in attainment counties from nonattainment counties, recovering an estimate of regulation-induced adaptation (RIA) akin to a difference-in-differences estimator. Ultimately, we embed our estimates into our analytical framework, combined with an estimate of the marginal damages of ozone from the literature, allowing us to calculate a back-of-the-envelope measure of the welfare effects of the additional adaptation induced by the NAAQS regulation.

While our empirical analysis focuses on a negative production externality—ambient ozone—regulation-induced adaptation may occur in any context where (i) the corrective policy reduces the market failure of interest, by directly targeting the relevant outcome, and (ii) climate change would otherwise exacerbate the market failure. Among many possible examples, consider existing programs and policies intended to correct the under-provision of vaccines to individuals, which can provide potentially large external benefits (White 2021). Climate change may increase the incidence or severity of disease outbreaks.[5] Individuals may respond to this increase by taking advantage of existing vaccine provision programs. That is, the existence of the vaccine provision program allows (induces) these individuals to engage in adaptive behavior, incidentally attenuating the impact of climate change. Similarly, consider institutions to correct the under-provision of public safety, such as government-maintained law enforcement agencies. Increasing temperatures may increase the probability of violence or unlawful activity (e.g., Ranson 2014; Mukherjee and Sanders 2021; Hsiang et al. 2013), but individuals may respond to this increase by calling on existing law enforcement to deter or reduce the severity of incidents, attenuating the climate impact.[6]

To understand the mechanism behind regulation-induced adaptation in our setting, consider a location where emissions of ozone precursor pollutants—Nitrogen Oxides (NOx) and Volatile Organic Compounds (VOCs)—are under control in the baseline. If a rise in temperature leads to more intense ozone formation and the violation of the NAAQS, economic agents will be designated as in nonattainment and pressured by the U.S. Environmental Protection Agency (EPA) to adopt pollution abatement strategies to reduce emissions of NOx and VOCs, and ultimately ambient ozone concentration. Since those actions would have to be taken not because of higher ozone precursor emissions but rather higher

---

[5] For example, warmer winters are associated with milder influenza seasons, but often lead to a more severe influenza season the following winter (Towers et al. 2013).

[6] Notice that defined in this way, RIA is not the regulator responding directly to climate change by, e.g., amending existing regulation or policy, but individual economic agents who are taking advantage of existing regulation or policy to adapt to the effects of a changing climate.

temperatures, we refer to the resulting decline in ozone levels as adaptation to climate change induced by the ozone NAAQS.[7] At the end of the day, in addition to smoothing out "status quo" pollution shocks, this existing Clean Air Act (CAA) regulation may encourage behavioral adjustments that also attenuate the pollution shocks triggered by climate change.

Our results demonstrate that existing policies unrelated to climate change can indeed facilitate adaptation, and the magnitude of the effect is of economic significance. In the absence of adaptation, a 1 °C increase in temperature would increase the ambient ozone concentration in nonattainment counties by 1.99 parts per billion (ppb), on average. Adaptation reduces this impact by 0.64 ppb, with 0.33 ppb due to regulation-induced adaptation (RIA). In other words, adaptation reduces the climate impact on ozone by about one third in nonattainment counties, with over half of the effect attributable to RIA. To put this effect in perspective, a 1.5 °C temperature increase—the midpoint of the representative concentration pathway (RCP) 4.5 and 8.5 warming scenarios for mid-century—would increase ozone by approximately 3 ppb in the absence of adaptation, but only 2 ppb once accounting for adaptation, with 0.5 ppb of this decrease due to RIA. Combined with an estimate of the social costs of ozone increases from the literature (Deschenes et al. 2017), our estimates would translate to between $794–908 million (2015 USD) per year in total adaptation welfare benefits by mid-century depending on the warming scenario (i.e., RCP 4.5 or 8.5), with $412–471 million attributable to the regulation-induced adaptation co-benefit of the NAAQS. For comparison, the cost of reducing the current NAAQS threshold by 1 ppb is $296 million per year (USEPA 2015b), which, taken together, implies a net welfare co-benefit of RIA ranging between $275–314 million per year..

Importantly, corresponding RIA measures for other key outcomes of local economic activity—employment and wages—are precise zeros, suggesting that our RIA measure captures differential responses to regulation rather than differences in other county-level drivers of emissions. Additionally, sample restrictions based on persistent vs. changing attainment status provide supportive evidence that our results are not driven by a sub-set of counties, and that the parallel trends assumption is satisfied. Our findings are robust to a wide variety of sample restrictions and specification checks, such as: accounting for competing regulations on ozone precursors, allowing for differential responses based on counties' proximity to the NAAQS nonattainment threshold, employing alternative climate measurements, allowing agents to have longer periods of adjustment to climatic changes, allowing for instantaneous adaptation from ozone alert days, among others. We also find suggestive evidence that regulation-induced adaptation is greater on days when temperature is higher (and higher ozone concentrations would thus be more likely, *ceteris paribus*), when local beliefs in the existence of climate change are stronger, and when the chemical

---

[7] By definition, climate adaptation involves adjusting to or coping with climatic change with the goal of reducing our vulnerability to its harmful effects. So, this is not a new use of the term climate adaptation. In the context of responses to natural disasters, for example, Kousky (2012) explains that "[t]he negative impacts of disasters can be blunted by the adoption of risk reduction activities. (...) [T]he hazards literature (...) refers to these actions as mitigation, whereas in the climate literature, mitigation refers to reductions in greenhouse gas emissions. The already established *mitigation measures* for natural disasters *can be seen as adaptation tools* for adjusting to changes in the frequency, magnitude, timing, or duration of extreme events with climate change." (p. 37, our highlights).

composition of the local atmosphere is "limited" in either of the two ozone precursor pollutants.[8]

This study makes three main contributions to the literature. *First*, it provides an analytical framework and credible empirical evidence that non-climate policies correcting existing market failures can be used as a buffer to climate shocks while also inducing climate adaptation. When the outcome of interest arises from market failures, and climate change would exacerbate those failures (e.g., Goulder and Parry 2008; Bento et al. 2014), existing non-climate policies may be able to smooth out the climate-exacerbated impacts and induce adaptation.[9] In contrast, prior research had highlighted *perverse* adaptation incentives generated by existing non-climate policies due to distortion of private behavior—e.g., Annan and Schlenker (2015) show that farmers may not engage in the optimal protection against extreme heat when crop losses are covered by the federal crop insurance program. *Second*, it demonstrates that existing government policy can also provide a catalyst for adaptation. Previous work had examined the role of market forces or private responses in adapting to climatic changes (e.g., Barreca et al. 2016), but private incentives may be limited in scope or distribution. *Third*, it points out a nontrivial incidental *co-benefit* of the Clean Air Act (CAA)—climate adaptation. Prior literature had analyzed the impacts of the CAA on air quality itself (e.g., Henderson 1996; Auffhammer and Kellogg 2011; Deschenes et al. 2017), and a variety of other economic outcomes (see a recent review by Aldy et al. 2020), including unintended consequences (e.g., Becker and Henderson 2000; Gibson 2019), but interactions between existing CAA regulations and climate change had been overlooked.

The paper proceeds as follows. Section 2 presents our analytical framework to understand how existing government regulations and policy may affect adaptation to climate change. Section 3 provides a background on the NAAQS for ambient ozone, ozone formation, and the data used in our empirical analysis. Section 4 introduces the empirical strategy; Sect. 5 reports and discusses the results; and Sect. 6 concludes.

2 Analytical Framework

The creation of new regulations can often prove politically or technologically infeasible, but existing regulations may mimic key incentives of a new regulation. In the context of climate change, several global climate policy architectures—basically new regulations—have been proposed over the years (e.g., Nordhaus 2019; Aldy and Zeckhauser 2020). Nevertheless, because of free-riding concerns, political polarization, and disagreement over the distribution of the costs of climate change mitigation, it has proven difficult to convince countries to join into an international agreement with significant emission reductions, or to enact federal legislation addressing climate change.

Recognizing the difficulty of implementing first-best climate policy, and the urgency in tackling the challenges of climate change, Goulder (2020) advocates for considerations

---

[8] To simplify our analytical framework, we follow Auffhammer and Kellogg (2011) and represent ozone formation by a Leontief-like production function. However, we recognize the complexity of ozone formation and run heterogeneity analysis by the composition of the local atmosphere. Additional reductions in the limiting precursor pollutant will *typically* lead to a larger overall reduction in ambient ozone concentrations.

[9] In the same spirit, Mullins and White (2020) find that the improved access to primary care services provided by the publicly-funded Community Health Centers rolled out across U.S. counties in the 1960 s and 1970 s moderated the heat-mortality relationship by 14.2 percent.

of political feasibility and costs of delayed implementation in the choice of climate policy. Second-best policies may be socially inefficient, but if they are politically feasible for near-term implementation, they might move up in the ordering of the policies considered by the federal government, akin to the discussion by Goulder (2020) in the context of climate policies.[10] In this study, we demonstrate that under certain conditions existing government regulations are already providing incentives for producers and consumers to adapt to climate change—much like a second-best policy—and argue that policymakers should take these co-benefits into consideration when enforcing or revising them.

2.1 The Nature of Existing Regulations Influencing Adaptation

To understand how existing "smoothing" institutions, policies, and regulations may induce climate adaptation, consider a simple formalization using a static analytical framework with a representative agent in the spirit of, e.g., Bovenberg and Goulder (1996) and Goulder et al. (1999). Assume that this agent enjoys utility from both a consumption good, Y, and an emissions-producing consumption good, X, with E the economy-wide emissions concentration from producing X.[11] The agent's utility function is given by:

$$U = u(X, Y) - \phi(E), \tag{1}$$

where $u(.)$ is utility from non-external goods and is quasi-concave, $\phi(.)$ is disutility from the economy-wide concentration of emissions and is weakly convex, and we assume additive separability of terms.[12] The representative agent competitively produces both X and Y using a fixed (exogenous) endowment of labor, L, as the only factor of production. Furthermore, assume that the marginal product of labor is constant in each industry, and normalize output such that marginal products—and thus wage rate—is unity, implying that the unit cost of producing X or Y is also unity. Additionally, assume that the emissions produced per unit of X is e, such that the economy-wide level of emissions, E, is equal to eX.[13] The agent's budget constraint is thus:

$$p_X X + Y = L + G, \tag{2}$$

where p_X is the demand price of X (equal to unity in the absence of any smoothing policy), L is the exogenous endowment of labor, and G is a lump-sum government transfer to the

---

[10] Many other second-best policies have been implemented around the world. The economic rationale has been laid out many decades ago (Lipsey and Lancaster 1956). In the context of climate change, a prominent example in the United States is the corporate average fuel economy (CAFE) standards. A first-best policy would be taxing tailpipe emissions directly.

[11] Note that E refers to the emissions of, e.g., a local pollutant and not greenhouse gas emissions. As this is a representative agent model, all production, consumption, and emissions can be considered local to the agent; in our empirical context this would be interpreted as local production causing local emissions, i.e., within the same county. In other contexts, this could be, e.g., a metropolitan area, state, or transport region. Furthermore, the use of local pollution emissions is without loss of generality, as the same framework would apply to any external output produced in proportion to X—positive or negative—where its creation or economy-wide level is somehow impacted by climate change.

[12] For the sake of simplicity in exposition we will focus on a negative externality, as in our empirical context, though this is without loss of generality, as all concepts and insights would similarly apply to the context of a positive externality by simply reversing the sign on ϕ.

[13] This implies that reductions in emissions can only be achieved by reducing production of X or through abatement activities which incur costs equivalent to reducing production of X.

agent equal to any revenue raised through the chosen smoothing policy (zero in the absence of any such policy). The representative agent chooses X and Y to maximize utility subject to this budget constraint, taking external damages as given.

First, consider a scenario in which the chosen smoothing policy is a corrective "quota"-based regulation imposed on emissions above a certain concentration, as with the NAAQS in our empirical setting.[14] That is, the government defines some threshold, $\bar{E}$, above which they impose a (virtual) tax of t_E on each additional unit of E. Thus,

$$G = \begin{cases} t_E(E - \bar{E}), & \text{if } E > \bar{E}. \\ 0, & \text{otherwise.} \end{cases} \tag{3}$$

and similarly, profit per unit of X would be:

$$\begin{cases} p_X - \{1 + t_E e\}, & \text{for each unit of } X > \bar{X}. \\ p_X - \{1\}, & \text{otherwise.} \end{cases} \tag{4}$$

where $\bar{X} = \frac{\bar{E}}{e}$ is the implicit "production threshold" arising from the regulation, and profits in equilibrium are equal to zero. The corrective regulation thus raises the marginal cost of X—for any production at or above $\bar{X}$—inducing output substitution towards the now comparatively more profitable production of Y.

Now, consider this same scenario but additionally assume that climate interacts with the economy-wide level of emissions by allowing E to be conditional on climate, c, that is, $E \equiv E(c) = e(c)X$. Thus, for the *same level* of existing regulation, t_E, under an increasing climate the representative agent would potentially face a more stringent constraint on their production of X, and would re-optimize to maximize profits such that $X_c \leq X_0$. Notably, this re-optimization would only occur if the agent were constrained by the regulation's threshold; if $E_0 \leq E_c \leq \bar{E}$, the regulation would remain non-binding and the agent would observe a "silent" increase in the level of economy-wide emissions. In other words, if the pre-existing corrective policy is binding (or becomes binding in the presence of climate change) it would induce behavioral adjustments, i.e., additional reductions in X, in response to an increasing climate—that is, regulation-induced adaptation.

Let us compare a scenario with no corrective smoothing regulation, denoted with superscript N, against a scenario with a corrective smoothing regulation, with superscript R. For a marginal change in climate, dc, the general equilibrium welfare effect of regulation-induced adaptation (RIA) consists of two key components (see Appendix C.1 for a proof):

$$\frac{1}{\lambda}\frac{dV}{dc}\Delta R = \underbrace{-\frac{\phi'}{\lambda}}_{\substack{Marginal \\ Damages}} \underbrace{\left(\frac{dE^R}{dc} - \frac{dE^N}{dc}\right)}_{RIA}, \tag{5}$$

where $\frac{1}{\lambda}\frac{dV}{dc}$ is the change in welfare due to an incremental change in climate, ΔR denotes the discrete change from a context without a binding regulation on E to a context with one, and importantly: (i) $\frac{\phi'}{\lambda}$ is the monetized marginal damages of the emissions concentration,

---

[14] Again, the assumption here of a specific policy type is without loss of generality—any corrective policy, such as a standard Pigouvian-style tax or Coasian permit-based policy would yield similar overall results.

while (ii) $\frac{dE^R}{dc}$ and $\frac{dE^N}{dc}$ reflect the change in the economy-wide level of emissions due to a changing climate with and without regulation, respectively. Thus, with an estimate of $\frac{\phi'}{\lambda}$ from the literature (e.g., Deschenes et al. 2017, provide an estimate of the WTP to avoid a marginal increase in ambient ozone), and our own econometrically recovered estimates of $\frac{dE^R}{dc}$ and $\frac{dE^N}{dc}$, we can calculate the welfare "co-benefit" of the pre-existing NAAQS regulation as the monetized value of regulation-induced adaptation. In the following subsection, Fig. 1 presents a schematic representation of regulation-induced adaptation in nonattainment counties, relative to any actions taken by attainment counties.

Notably, there may be systematic deviations between regulated and unregulated regions (or even for the same region across different time periods) that could lead to level differences in "off the shelf" estimates of $\frac{dE^R}{dc}$ and $\frac{dE^N}{dc}$ which would in turn contaminate any welfare calculation. For example, in our empirical setting, counties are only constrained by the NAAQS if their ozone concentration levels are above the set threshold—thus, by definition, regulated counties will have inherently higher levels of baseline emissions and any increases in climate will in turn lead to comparatively higher levels of new ozone formation, before accounting for adaptation. At the same time, there may be other, exogenous, drivers of adaptation that could affect both regulated and unregulated counties. In order to account for these and other possible issues, we first econometrically estimate overall adaptation for both regulated and unregulated counties—in the same estimating equation—and use our estimates of *adaptation* in regulated and unregulated counties as the welfare parameters $\frac{dE^R}{dc}$ and $\frac{dE^N}{dc}$ respectively, de-facto "differencing out" any level differences as well as any adaptation that is exogenous to the regulation of interest.

Not every pre-existing policy or regulation with climate interactions will induce adaptation, however, as has been documented in prior literature (e.g., Annan and Schlenker 2015). Thus, it is useful to examine under what conditions we can expect such regulations to induce or inhibit adaptation. As shown above, policies which correct a pre-existing market failure will incidentally induce adaptation if that market-failure has climate interactions. In Appendix C.2, we extend our analytical framework to show how and why the opposite also holds true—policies or regulations that distort private behavior will inhibit adaptation if the distortion has climate interactions. We additionally extend the original framework to examine input, rather than output, regulations on emissions or other externalities—showing that even when the output has climate interactions, if the input lacks any climate interaction, then the regulation will fail to induce adaptation. Specifically, while such input regulations may reduce climate *impacts*—for example, by reducing the baseline level of precursor emissions—if the input(s) lack clear climate interactions then the regulation would not create any incentive for agents to adjust their behavior in response to climate change. That is, the regulation would not induce any climate *adaptation*.

2.2 A Schematic Representation of the Framework for Ambient Ozone and NAAQS

We apply the analytical framework in an empirical setting, focusing on the existing Clean Air Act (CAA) regulation—specifically, the National Ambient Air Quality Standard (NAAQS) for ozone. With the CAA Amendments of 1970, the EPA was authorized to set up and enforce a NAAQS for ambient ozone.[15] Since then, a nationwide network of

---

[15] For further details of the ozone NAAQS see Appendix A.1.

air pollution monitors has allowed EPA to track ozone concentrations, and a threshold is used to determine whether pollution levels are sufficiently dangerous to warrant regulatory action.[16] Counties with ozone levels exceeding the NAAQS threshold are designated as in "nonattainment" and the corresponding state is required to submit a state implementation plan (SIP) outlining its strategy for the nonattainment county to reduce air pollution levels in order to reach compliance.[17] Depending on the severity of the exceedance, counties are given between 3- and 20-years to reach compliance, but in all cases, counties must show active progress within the first three years (USEPA 2004).[18] In cases of persistent nonattainment, the CAA mostly mandates command-and-control regulations, requiring that plants use the "lowest achievable emissions rate" technology (LAER) in their production processes. Furthermore, if pollution levels continue to exceed the standards or if a county fails to abide by the approved plan, sanctions may be imposed on the county in violation, such as retention of funding for transportation infrastructure.

To make the concept of regulation-induced adaptation as clear as possible in the context we are studying, we use the schematic representation depicted in Fig. 1. In this representation, we follow Auffhammer and Kellogg (2011) and use a simplified characterization of the process of ozone formation as a Leontief-like production function using two inputs—NOx and VOCs.[19] In Panel A, the y-axis represents the regulated output—ozone formation—and the x-axis represents a composite index $I(.)$ of those two inputs, whose levels move along the production function $F(I(\text{NOx,VOCs}), \text{Climate})$ represented by the upward-sloping black line. $F(I(\text{NOx,VOCs}), \text{Climate})$ is equivalent to $E(c) = e(c)X$ in the formalization above. The blue horizontal line represents the maximum ambient ozone concentration, $\bar{E}$, a county may reach while still complying with the NAAQS for ozone. Above that threshold, a county would be deemed out of compliance with the standards, or in nonattainment. Panel B illustrates the Leontief-like production function of ozone with respect to its precursors, VOCs and NOx, on the x- and y-axis, respectively, and resulting ozone "isoquant" curves increasing up and to the right.[20]

Assume that an ozone monitor is sited in a county that is initially complying with the standards, as in point A. Moreover, suppose for simplicity that emissions of ozone precursors are such that ozone levels are initially under control, but then temperature rises. Because Panel A depicts a bidimensional diagram representing ozone as a function of $I(\text{NOx,VOCs})$—taking climate as given—an increase in temperature shifts the production function upward and to the left. This new production function under climate change

---

[16] Exposure to ambient ozone has been causally linked to increases in asthma hospitalization, medication expenditures, and mortality, and decreases in labor productivity (e.g., Neidell 2009; Moretti and Neidell 2011; Zivin and Neidell 2012; McGrath et al. 2015; Deschenes et al. 2017).

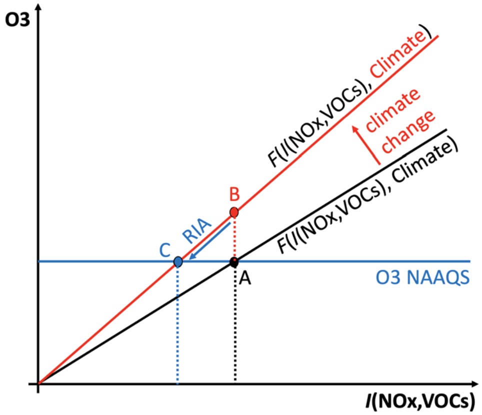
[17] Appendix Table A1 details the current and historical thresholds used to determine nonattainment status under the prevailing NAAQS.

[18] In later robustness checks we examine the sensitivity of our estimates to shortening or lengthening the time counties are given to reach compliance, finding no statistical or economically meaningful difference. We thus opt to follow the EPA's regulatory schedule by using a 3-year lag of nonattainment status.

[19] Naturally, ozone production is much more complicated. Notably the relationship varies significantly with the composition of the atmosphere and physical forcings. The exact relationship is often times proxied by the ratio of VOCs to NOx, but mixing ratios and the reactivity of available VOCs add a lot of uncertainty to the actual production (e.g., Sillman and He 2002). To account for these nuances in ozone formation, in our empirical analysis we explore the heterogeneity of our main effects to the composition of the local atmosphere—VOC-limited vs. NOx-limited.

[20] In reality, the ozone isoquants might bend inward, especially on the vertical (NOx) axis. There is a fairly large region in which NOx decreases actually increases ozone.

Panel A. Ozone, Ozone Precursors, and Climate



Panel B. Ozone Precursors (Inputs)

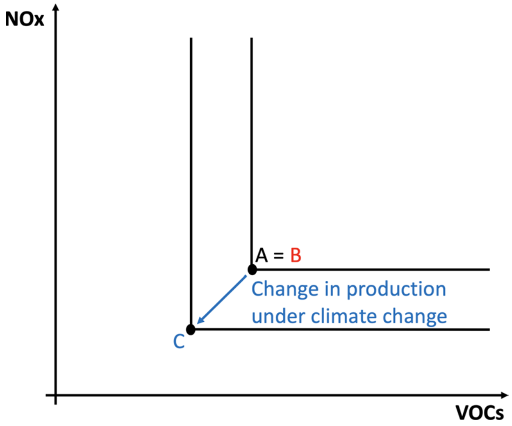


Fig. 1 Conceptual framework on regulation-induced adaptation. *Notes:* This figure provides a schematic representation of the conceptual framework used in our analysis. In this representation, we follow Auffhammer and Kellogg (2011) and use a simplified characterization of ozone formation as a Leontief-like production function using two inputs—NOx and VOCs. In reality, ozone formation is much more complicated, as discussed in the text. In the top panel, the *y*-axis represents the output—ozone formation—and the *x*-axis represents a composite index *I*(.) of the two inputs—NOx and VOCs—whose levels move along the linear production function *F*(*I*(NOx,VOCs), Climate) represented by the upward-sloping black curve. The blue horizontal line represents the maximum ambient ozone concentration a county may reach while still complying with the NAAQS for ambient ozone. In point *A*, a county is complying with the standards. When average temperature rises, the *chemical* production function shifts upward and to the left, and is now represented by the red upward-sloping curve. For the *same* level of the index *I*(NOx,VOCs), ozone concentration increases to point *B*. Because the county is now out of compliance with the NAAQS, they are required to make adjustments in their production processes to comply with the standards. As they take steps to reduce emissions of ozone precursors to reach attainment—moving along the new *chemical* production function curve until point *C*—those economic agents are in fact adjusting to a changing climate, which is by definition adaptation to climate change. Indeed, as Panel B shows, agents must reduce the production of ozone precursors in order to reach point *C*. NOx and VOCs are complements in the production of ozone. *RIA* stands for *regulation-induced adaptation*, and represents the adaptation to climate change triggered by the existing NAAQS regulation under the Clean Air Act

is represented by the red upward-sloping line. Because we assumed emissions of ozone precursors were initially under control, an increase in average temperature raises ozone concentration for the same level of the index I(NOx,VOCs), reaching point B. Since the ozone concentration is now above the NAAQS threshold, the county is designated as out of attainment, and firms are pressured to make adjustments in their production process to comply with the air quality standards in the near future, usually three years after a county receives the nonattainment designation.

Notice that firms need to respond to the regulation not because they were careless in controlling emissions in the baseline, but rather because climate has changed. As they take steps to reduce emissions to reach attainment, moving along the new production function until point C as shown in both Panel A and B, those economic agents are in fact adjusting to a changing climate. This new production function (technology) may have a cost advantage in the abatement of ozone precursors in the state of the world with climate change. Thus, the agents are adapting to climate change because of the ozone NAAQS regulation, that is, they are engaging in regulation-induced adaptation.[21]

3 Data Description

Ambient ozone is one of the six criteria pollutants regulated under the existing Clean Air Act. However, unlike other pollutants, it is not emitted directly into the air. Rather, it is formed by Leontief-like chemical reactions between nitrogen oxides (NOx) and volatile organic compounds (VOCs), under sunlight and warm temperatures. Because ambient ozone is affected by both climate and regulations, and high-frequency data are available since 1980, this is an ideal setting to study regulation-induced adaptation. In Appendix A, we provide further details regarding the ozone standards, ozone formation and the data.

3.1 NAAQS, Ozone Pollution, and Climate: Background and Data

NAAQS data. For data on the Clean Air Act nonattainment designations associated with exceeding the NAAQS for ambient ozone, we use the EPA Green Book of Nonattainment Areas for Criteria Pollutants, which provides an indicator of nonattainment status for each county-year in our sample. In our empirical analysis, we use the nonattainment status lagged by three years because EPA gives counties with heavy-emitters at least three years to comply with NAAQS for ambient ozone (USEPA 2004, p. 23954).[22]

---

[21] Ambient ozone concentration is a negative externality. For completeness, public policy can also induce adaptation to climate change in addressing positive externalities. Besides the social desirability of increasing the level of those outcomes, such policies can create a co-benefit of adjusting to a changing climate. One example is the Medicaid-covered influenza vaccination. Severe influenza seasons are likely to emerge with global warming (Towers et al. 2013), but publicly-funded annual vaccination allows Medicaid beneficiaries to cope with climatic changes. This is in addition to the herd-immunity impact of influenza vaccination (White 2021). Thus, the concept of policy-induced adaptation is quite broad, and incentives affecting adaptive behavior are already in place in a variety of policies implemented around the world.

[22] EPA allows nonattainment counties with polluting firms between 3 to 20 years to adjust their production processes. Nonattainment counties are *"classified as marginal, moderate, serious, severe or extreme (...) at the time of designation"* (USEPA 2004, p. 23954). They must reach attainment in: *"Marginal—3 years, Moderate—6 years, Serious—9 years, Severe—15 or 17 years, Extreme—20 years"* and show active progress within the first three years (USEPA 2004, p. 23954).

Specifically, with regards to nonattainment status, if any monitor within a county exceeds the NAAQS, EPA designates the county to be out of attainment (USEPA 1979, 1997, 2004, 2008, 2015a). While the structure of enforcement is dictated by the CAA and the EPA, much of the actual enforcement activity is carried out by regional- and state-level environmental protection agencies, with local agencies having discretion over enforcement as long as they are within attainment for the NAAQS. Regional EPA offices do, however, conduct inspections to confirm attainment status and/or issue sanctions when a state's enforcement is below required levels, and assist states with major cases. Thus, while there may be heterogeneity in local enforcement for nonattainment counties, we would expect that those counties achieve at least the minimum level of increased regulation mandated by the EPA.

Ozone data. For ambient ozone concentrations, we use daily readings from the nationwide network of the EPA's air quality monitoring stations. Following Auffhammer and Kellogg (2011) and the regulatory design implemented by the Clean Air Act for designating a county as out of attainment, in our preferred specification we use an unbalanced panel of ozone monitors and make only two restrictions to construct our analysis sample. First, we include only monitors with valid daily information. According to EPA, daily measurements are valid for regulation purposes only if (i) 8-hour averages are available for at least 75 percent of the possible hours of the day, or (ii) daily maximum concentration is higher than the standard. Second, as a minimum data completeness requirement, for each ozone monitor we include only years for which at least 75 percent of the days in the typical ozone monitoring season (April–September) are valid; years having concentrations above the standard are included even if they have incomplete data.[23] Our final sample consists of valid ozone measurements for a total of 5,139,129 monitor-days.[24]

Weather data. For climatological data, we use daily measurements of maximum temperature as well as total precipitation from the National Oceanic and Atmospheric Administrations's Global Historical Climatology Network databse (NOAA 2014). This dataset provides detailed weather measurements at over 20,000 weather stations across the country. We use information from 1950 to 2013, because we need 30 years of data prior to the period of analysis to construct a moving average measure of climate.[25] The weather stations are typically not located adjacent to the ozone monitors. Hence, we match ozone monitors to nearby weather stations using a straightforward procedure.[26]

---

[23] The typical ozone monitoring season around the country is April–September, but in fact it varies across states. Appendix Table A2 reports the season for each state. In our empirical analysis we use only the common ozone season across all states, which includes the six months from April through September.

[24] Appendix Figure A1 depicts the evolution of ambient ozone monitors over the three decades in our data, and illustrates the expansion of the network over time. Appendix Table A3 provides annual summary statistics on the ozone monitoring network. The number of monitors increased from 1361 in the 1980 s to 1851 in the 2000 s. The number of monitored counties also grew from 585 in the 1980 s to 840 in the 2000 s. While Muller and Ruud (2018) find that compliance with the NAAQS for ambient ozone is not consistently associated with network composition, Grainger et al. (2019) provide evidence that local regulators do avoid pollution hotspots when siting new ozone monitors. Later, as a robustness check, we show qualitatively similar results for a semi-balanced panel of ozone monitors.

[25] Appendix Figure A2 presents the yearly temperature fluctuations and overall trend in climate for the contiguous US as measured by these monitors, relative to a 1950–1979 baseline average temperature.

[26] Using information on the geographical location of ozone monitors and weather stations, we calculate the distance between each pair of ozone monitor and weather station using the Haversine formula. Then, for every ozone monitor we exclude weather stations that lie beyond a 30-km radius. Moreover, for every ozone monitor we use weather information from only the closest two weather stations within the 30-km radius. Appendix Figure A3 illustrates the proximity of our final sample of ozone monitors to these matched weather stations. Once we apply this procedure, we exclude ozone monitors that do not have any weather stations within 30 km. As will be discussed later, our results do not seem sensitive to these choices.

3.2 Basic Trends in Pollution, Attainment Status, and Weather: Implications for the Importance of Regulations

To give a sense of the data, Fig. 2 illustrates the evolution of ozone concentrations and the proportion of counties in nonattainment over our sample period, while Fig. 3 does the same for our two components of daily temperature—climate norms and weather shocks.

Ozone concentrations and nonattainment designations. Figure 2, Panel A, depicts the annual average of the highest daily maximum ambient ozone concentration recorded at each monitor from 1980 to 2013 in the United States. The sample is split according to whether counties were in or out of attainment with the NAAQS for ambient ozone. Counties out of compliance with the NAAQS experienced, on average, a steeper reduction in the daily maximum ozone levels than counties in compliance.[27]

Figure 2, Panel B, shows that as ambient ozone concentrations fell, the number of counties out of attainment also declined. Notice that when the 1997 NAAQS revisions were implemented in 2004 after litigation, the share of counties out of attainment increased more than 50 percent. Such a jump is not observed in the implementation of the 2008 revision, however. In the latter case, the share of counties in nonattainment remained stable around 30 percent. Appendix Figure A5 shows that most counties out of attainment were first designated in nonattainment in the 1980’s. The map displays concentrations of those counties in California, the Midwest, and in the Northeast. Nevertheless, a nontrivial number of counties went out of attainment for the first time in the 1990’s and 2000’s.

Decomposing temperature into long-run climate norms and short-run weather shocks. In order to disentangle variation in weather versus climate, we decompose average temperature into a climate norm—a 30-year monthly moving average (MA) following (WMO 2017), and a weather shock—the daily deviation from the norm.[28] Figure 3, Panel A, plots the annual average of the 30-year MA in the dotted line, as well as a smoothed version of it in the solid line; note that due to the nature of the MA, this takes into account information since 1950. Panel B plots the annual average of the shocks. Notice that the average deviations from the 30-year MA are bounded around zero, with bounds relatively stable over time, suggesting little changes in the variance of the climate distribution.[29] Using our final sample, not surprisingly Appendix Figure A7 shows that ambient ozone is closely related to both components of temperature, which we examine more formally in the empirical analysis.

---

[27] Appendix Figure A4 further compares similar trends in ozone levels with the updated 1997, 2008, and 2015 NAAQS levels which, while much lower, are based instead on the observed 4th highest 8-hour average ambient ozone concentration.

[28] Our decomposition of meteorological variables into a 30-year moving average (norms) and deviations from it (shocks) is a data filtering technique to separate the “signal” from the “noise.” This should not be confused with a moving-average model of climate change. We average temperature over 30 years because it is how climatologists usually define climate normals, though other filtering techniques could be used. Interestingly, when we run robustness checks regarding a potential measurement error of the temperature norm related to the window of the moving average, we find suggestive evidence that 30 years is approximately where the error is minimum. In further robustness checks, we examine the sensitivity of our results to using a *daily* rather than monthly moving-average.

[29] Figure 3 is constructed using the comprehensive sample of NOAA weather stations in order to provide a sense of the climate norms and weather shocks that is nationally representative. Appendix Figure A6 presents a similar illustration to Fig. 3 using our final sample of weather monitors once matched to ozone monitors. Appendix Table A4 reports the summary statistics for daily temperature and our decomposed variables, for each year in our sample from 1980 to 2013.

4 Empirical Framework

In the empirical analysis, we focus on estimating the extent to which ozone concentration is affected by climate change under the NAAQS regulation, relative to a benchmark without (or lower levels of) regulation. The goal is to recover $\left(\frac{dE}{dc}^{R} - \frac{dE}{dc}^{N}\right)$ in Eq. (5), the measure of regulation-induced adaptation. Thus, with an estimate of $\frac{\phi'}{\lambda}$, the marginal damage of ozone pollution, from the literature (e.g., Deschenes et al. 2017), we are able to provide some back-of-the-envelope calculations regarding welfare changes.

We build upon a unifying approach to estimating climate impacts (Bento et al. 2020) which bridges the two leading approaches of the climate-economy literature identifying both weather and climate impacts in the same equation. Moreover, because our approach critically identifies adaptation by comparing how the *same* economic agents respond to both weather and climate variation, we are able to recover our measure of regulation-induced adaptation by comparing heterogeneous adaptation from counties in and out of attainment with the NAAQS for ozone without needing to make assumptions over preferences.[30] In contrast, previous studies have inferred adaptation *indirectly*, by flexibly estimating economic damages due to weather shocks—sometimes for different time periods and locations—then assessing climate damages by using shifts in the future weather distribution predicted by climate models (e.g., Deschenes and Greenstone 2011; Barreca et al. 2016; Auffhammer 2018; Carleton et al. 2019; Heutel et al., forthcoming). That implies an extrapolation of weather responses over time and space, which requires preferences to be constant across those dimensions, an assumption that can be challenging for reasons similar to the Lucas Critique (Lucas 1976).

As a first step to implement our approach, we decompose the observed daily maximum temperature into a climate norm and a daily weather shock. The norm is operationalized by the 30-year monthly moving average (MA), akin to the concept of climate normals used in climatology.[31] The shock is merely the deviation of the observed daily temperature from that norm. Because ozone formation is directly tied to temperature, as discussed in Sect. 3, the impact of temperature on ambient ozone is the focus of our analysis. Given that decomposition, we estimate the following equation:

$$\begin{aligned} Ozone_{it} = {} & \beta_N^W(Temp_{it}^W \times Nonattain_{c,y-3}) + \beta_N^C(Temp_{im}^C \times Nonattain_{c,y-3}) \\ & + \beta_A^W(Temp_{it}^W \times Attain_{c,y-3}) + \beta_A^C(Temp_{im}^C \times Attain_{c,y-3}) \\ & + X_{it}\gamma + \eta_{is} + \phi_{rsy} + \epsilon_{it}, \end{aligned} \tag{6}$$

where i represents an ozone monitor located in county c of NOAA climate region r, observed on day t, month m, season s (Spring or Summer), and calendar year y. Our

---

[30] In our context, adaptation could be driven by, for example, individuals responding to pollution information, firms adjusting to environmental regulation, and local regulators implementing federal laws. The estimation strategy should capture the sum of all responses together, without separating them out.

[31] To make this variable part of the information set held by economic agents at the time ambient ozone is measured, we lag it by one year. For example, the 30-year MA associated with May 1982 is the average of May temperatures for all years in the period 1952–1981. Therefore, economic agents should have had at least one year to respond to unexpected changes in climate normals at the time ozone is measured. Later, we discuss almost identical results for longer lags. Also, we use monthly MAs because it is likely that individuals recall climate patterns by month, not by day of the year. Indeed, broadcast meteorologists often talk about how a month has been the coldest or warmest in the past 10, 20, or 30 years, but not how a particular day of the year has deviated from the norm for that specific day. Later, we discuss qualitatively similar results when we use *daily* instead of *monthly* moving averages.

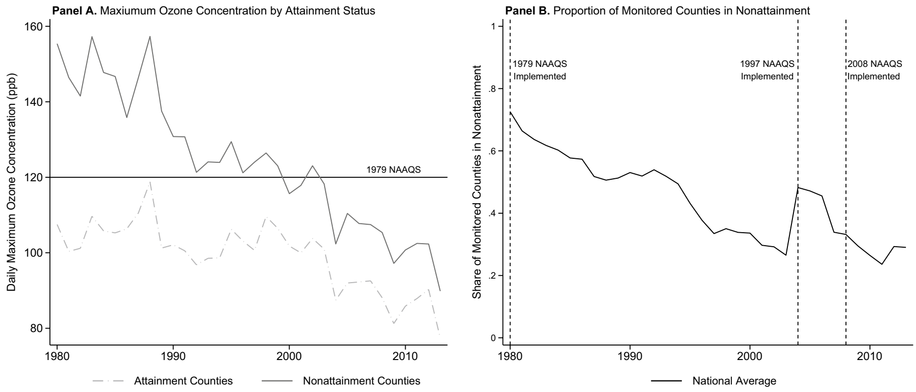


Fig. 2 Evolution of maximum ozone concentration and counties in nonattainment. *Notes:* This figure displays the evolution of maximum ambient ozone concentrations in the United States over the period 1980–2013 and the evolution of the proportion of counties violating the ambient ozone standards among the counties with ozone monitors. Panel (A) depicts daily maximum 1-hour ambient ozone concentrations over time (annual average), split by counties designated as in- or out- of attainment under the National Ambient Air Quality Standards (NAAQS). The 1979 NAAQS for designating a county's attainment status was based on an observed 1-hour maximum ambient ozone concentration of 120 parts per billion (ppb) or higher. Here we contrast this attainment status cutoff with the maximum yearly ozone concentrations of attainment and nonattainment counties. Appendix Figure A4 further compares these heterogeneous trends in ozone levels with the updated 1997 (implemented in 2004 due to lawsuits), 2008, and 2015 NAAQS levels. Panel (B) depicts the share of monitored counties that were out of attainment with the NAAQS for ozone during each year of our sample period. As can be clearly seen, this proportion has declined over time as the NAAQS regulations took effect. Also, observe that the policy change in 2004 resulted in many additional counties falling out of attainment, indicating that there was a nontrivial number of counties with ozone levels at the margin of nonattainment

analysis focuses on the most common ozone season in the U.S.—April to September, as mentioned in the background section—over the period 1980–2013. *Ozone* represents daily maximum ambient ozone concentration, $Temp^W$ represents the weather shock, and $Temp^C$ the climate norm. Hence, the response of ambient ozone to the temperature shock β^W represents the short-run effect of weather, and the response to the climate norm β^C reflects the long-run impact of climate. $Nonattain_{cy}$ denotes nonattainment designation, which is a binary variable equals to one if a county c is not complying with the NAAQS for ambient ozone in year y. Given the structure of fixed effects described below, the identifying variation regarding attainment status is essentially "within-county variation."[32] This variable is lagged by three calendar years because EPA allows counties with heavy polluters at least three years to comply with the ozone NAAQS, as discussed in the background section. X represents time-varying control variables such as precipitation—similarly decomposed into a norm and shock. Although less important than temperature, Jacob and Winner (2009)

---

[32] Because there is variation in the timing of nonattainment designations, but we have a never treated group (the persistent attainment counties), identification can rely on the weakest parallel trends assumption considered by Marcus and Sant'Anna (2021), which does not impose any restriction on pretreatment trends across groups. In fact, when there is a "reasonably large" number of never treated units—as is the case in our setting—that assumption can identify policy-relevant parameters even "if researchers are not comfortable with *a priori* ruling out nonparallel pretrends" (Marcus and Sant'Anna 2021, p. 251).

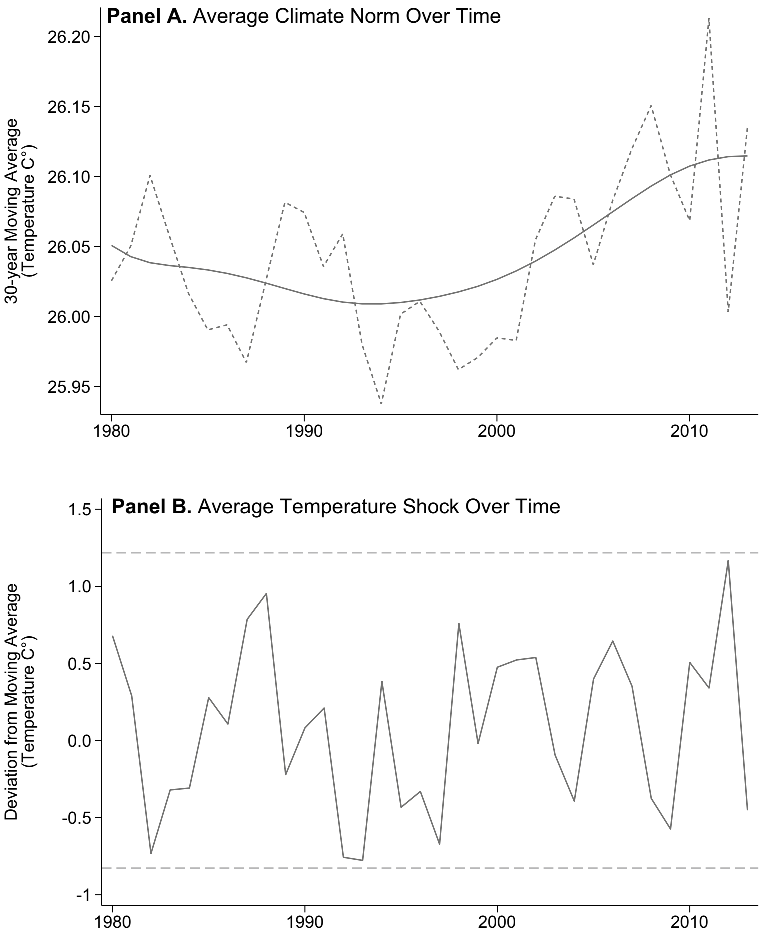


Fig. 3 Climate norms and shocks over the period of analysis (1980–2013). *Notes:* This figure depicts US temperature over the years in our sample (1980–2013), decomposed into their climate norm and temperature shock components. The climate norm (Panel A) and temperature shocks (Panel B) are constructed from a complete, unbalanced panel of weather stations across the US from 1950 to 2013, restricting the months over which measurements were gathered to specifically match the ozone season of April–September, the typical ozone season in the US (see Appendix Table A2 for a complete list of ozone seasons by state). Recall that the climate norm represents the 30-year monthly moving average of the maximum temperature, lagged by one year, while the temperature shock represents the difference between daily observed maximum temperature and the climate norm. The solid line in Panel (A) smooths out the annual averages of the 30-year moving averages, and the horizontal dashed lines in Panel (B) highlights that temperature shocks are bounded in our period of analysis. *Source*: Bento et al. (2023)

point out that higher water vapor in the future climate may decrease ambient ozone concentration.[33] η represents monitor-by-season fixed effects, ϕ climate-region-by-season-by-year

---

[33] Although temperature is the primary meteorological factor affecting tropospheric ozone concentrations, other factors such as wind and sunlight have also been noted as potential contributors. Later, we discuss qualitatively similar results for a subsample with information on wind speed and sunlight.

fixed effects, and ϵ an idiosyncratic term.[34] Standard errors are clustered at the county level.[35]

This approach has two key elements. The first is the decomposition of meteorological variables into two components: long-run climate norms and transitory weather shocks, the latter defined as deviations from those norms. This decomposition is meant to have economic content. It is likely that individuals and firms respond to information on climatic variation they have observed and processed over the years. In contrast, economic agents may be constrained in their ability to respond to weather shocks, by definition. As mentioned above, our measure of adaptation is the difference between those two responses by the *same* economic agents. In practice, we decompose temperature into a monthly moving average incorporating information from the past three decades, often referred to as climate normal, and a daily deviation from that 30-year average. This moving average is purposely lagged in the empirical analysis to reflect all the information available to individuals and firms up to, and including, the year prior to the measurement of the outcome variables.[36]

The second key element of our approach is identifying responses to weather shocks and longer-term climatic changes in the *same* estimating equation. We are able to leverage both sources of variation in the same estimating equation because of the properties of the Frisch–Waugh–Lovell theorem (Frisch and Waugh 1933; Lovell 1963). The deseasonalization embedded in the standard fixed-effects approach is approximately equivalent to the construction of weather shocks as deviations from long-run norms as a first step. Furthermore, there is no need to deseasonalize the outcome variable to identify the impact of those shocks (Lovell 1963, Theorem 4.1, p. 1001).[37] As a result, we do not need to saturate the econometric model with highly disaggregated time fixed effects; thus, we are able to also exploit variation that evolves slowly over time to identify the impacts of longer-term climatic changes.

We exploit plausibly random, daily variation in weather, and monthly variation in climate normals to simultaneously identify the impact of weather shocks and climate change on ambient ozone concentration. Identification of the weather effect is similar to the standard fixed effect approach (e.g., Deschenes and Greenstone 2007; Schlenker and Roberts 2009), with the exception that because we isolate the temperature shock as a first step, we do not need to include highly disaggregated time fixed effects (Frisch and Waugh 1933;

---

[34] In unreported analyses we examine specifications with alternative fixed effects structures, such as including latitude and longitude interacted with season-by-year, or replacing region-by-season-by-year with state-by-season-by-year. Estimates from our preferred, more parsimonious specification are similar in magnitude and significance to each of these alternatives.

[35] In later robustness checks we assess the sensitivity of our results to changes in our estimation of the standard errors: increasing the spatial dimension of the clustering to the state-level, adding a temporal-dimension via two-way clustering by both county and week, and estimation via county-level block bootstrap. All coefficients remain statistically significant at the 1% level regardless of the choice of cluster or bootstrap.

[36] A graphical representation of our decomposition is illustrated for Los Angeles county in 2013 in Appendix A.3 Figure A8, and over the entire sample period of 1980–2013 in Figure A9.

[37] "*Theorem 4.1: Consider the following alternative regression equations, where the subscript α indicates that the data have been adjusted by the least squares procedure with D as the matrix of explanatory variables: 1.* $Y = Xb_1 + D_{a1} + e_1$ *2.* $Y_\alpha = X_\alpha b_2 + e_2$*... 4.* $Y = X_\alpha b_4 + e_4$ *... The identity* $b_1 = b_2$ *reveals that inclusion of the matrix of seasonal dummy variables in the regression analysis is equivalent to working with least squares adjusted time series. The identity* $b_2 = b_4$ *reveals that it is immaterial whether the dependent variable is adjusted or not, provided the explanatory variables have been seasonally corrected*" (Lovell 1963).

Lovell 1963). Identification of the climate effect relies on plausibly random, within-season monitor-level monthly variation in lagged 30-year MAs of temperature after flexibly controlling for regional shocks at the season-by-year level.[38]

To better understand the identification of climate impacts, consider the following thought experiment that we observe in our data many thousands of times: take two months in the same location and season (Spring or Summer). Now, suppose that one of the months experiences a hotter climate norm than the other, after accounting for any time-varying fluctuations in, e.g., atmospheric or economic conditions that affected the overarching climate region at the season-by-year level. Our estimation strategy quantifies the extent to which this difference in the climate norm affected the ozone concentrations observed on that month. Therefore, this approach controls for a number of potential time-invariant and time-varying confounding factors that one may be concerned with, such as the composition of the local and regional atmosphere, or technological progress. Furthermore, note that because the monthly climate norm is operationalized as a 30-year moving average for that month, the climate norm is "updated" from year to year as the temperature from 31 years ago drops out, and the temperature from last year enters into the moving average. This updating feature of the MA also mimics the ideal "climate experiment" by, for example, making the April climate norm in one year appear more like the May climate norm. For instance, if the average temperature in April 31-years ago was particularly cold, while the average temperature in April of last year was particularly warm, the 30-year moving average climate norm in this year's April may be meaningfully warmer than last year's April climate norm. In other words, we identify agents' response to their new climate expectation using both within-season variation across months and year-to-year variation for the same month.

Our ultimate goal, however, is not just to identify adaptation via estimates of climate impacts vis-à-vis weather shocks, but to identify whether there is a *different* level of adaptation in nonattainment versus attainment counties. As the EPA was given substantial enforcement powers to ensure that the goals of the Clean Air Act were met, policy variation itself is plausibly exogenous conditional on observables and the unobserved heterogeneity embedded in the fixed effects structure considered in our analysis (see, e.g., Greenstone 2002; Chay and Greenstone 2005). In order to reach compliance, some states initiated their own inspection programs and frequently fined non-compliers. However, for states that failed to adequately enforce the standards, EPA was required to impose its own procedures for attaining compliance. The inclusion of monitor-by-season fixed effects allows us to control for the strong positive association observed in cross-sections among location of polluting activity, high concentration readings, and nonattainment designations while preserving inter-annual variation in attainment status for each individual monitor. Thus, the variation used in our analysis comes from both cross-sectional differences in attainment status between counties and from changes in status within the same county over time, as previously shown in Fig. 2: from attainment to nonattainment, or vice versa.

---

[38] Because the climate norm is a constructed variable, there may be a concern that measurement error in this variable could lead to attenuation of the estimated coefficient. In later robustness checks we examine this concern by implementing alternative lengths of the moving average, finding results that are statistically and economically similar across all MA lengths. Furthermore, as noted by Solon (1992) in his examination of the effect of parents' income on that of their child, using a longer moving-average should reduce any measurement error in this variable.

Measuring regulation-induced adaptation. Once we credibly estimate the impact of the two components of temperature interacted with county attainment status, we recover a measure of regulation-induced adaptation. The average adaptation in nonattainment counties is the difference between the coefficients β_N^W and β_N^C in Eq. (6). If economic agents engaged in full adaptive behavior, β_N^C would be zero, and the magnitude of the average adaptation in those counties would be equal to the size of the weather effect on ambient ozone concentration (for a review of the concept of climate adaptation, see Dell et al. 2014). Indeed, under full adaptive behavior, any unexpected increase in the climate norm would lead economic agents to pursue reductions in ozone precursor emissions to avoid an increase in ambient ozone concentration of identical magnitude to the weather effect in the same month of the following year.[39] In other words, agents would respond to "permanent" changes in temperature by adjusting their production processes to offset that increase in the climate norm. Unlike weather shocks, which influence ozone formation by triggering chemical reactions conditional on a level of ozone precursor emissions, changes in the 30-year MA should affect the level of emissions.

We can measure adaptation in attainment counties in the same way: $(\beta_A^W - \beta_A^C)$. This adaptation could arise from technological innovations, market forces, or regulations other than the NAAQS for ambient ozone.[40] Sources of this type of adaptation would be, for example, the adoption of solar electricity generation, which reaches maximum potential by mid-day, when ozone formation is also at high speed, or other existing policies and regulations that have interactions with both ozone and climate, such as incentives to adopt low or zero emissions vehicles, which may reduce precursor emissions during rush-hours when ozone formation is typically at its highest.[41]

Once we have measured adaptation in both attainment and nonattainment counties, we can express adaptation induced by the NAAQS for ambient ozone matching Eq. (5) as the difference:

$$RIA \equiv \underbrace{(\beta^W - \beta^C)}_{dE/dc} \times \underbrace{(\mathbb{1}_N - \mathbb{1}_A)}_{\Delta R} = (\beta_N^W - \beta_N^C) - (\beta_A^W - \beta_A^C). \tag{7}$$

Because our RIA measure is analogous to a difference-in-differences parameter, it must satisfy a parallel trends assumption on the estimates of adaptation for nonattainment and attainment counties. To provide suggestive evidence supporting that assumption, we re-run Eq. 6 for sub-samples based on attainment status to examine pre-trends, as well as other outcomes that capture key dimensions of local economic activity—employment and

---

[39] Again, later we consider cases where economic agents can take a decade or two to adjust. Because EPA may give counties with heavy emitters up to two decades to comply with the ozone NAAQS, as discussed in the background section, adaptive responses many years after agents observe changes in climate norms may be plausible. Interestingly, we will find almost identical results.

[40] Indeed, EPA mandates "best available control technology" (BACT) to curb emissions of local pollutants from large point sources even in attainment counties. As mentioned earlier, EPA mandates the more stringent "lowest achievable emissions rate" (LAER) technology in nonattainment counties. Abatement costs are considered in formulating BACT standards, but not LAER standards.

[41] For regulatory purposes, all the EPA considers is the observed measurement of ozone concentration by the pollution monitor, irrespective of weather conditions. It is important to mention, however, that EPA considers weather conditions when determining trends in ozone concentrations. In fact, EPA uses statistical models to adjust for the variability in seasonal ozone concentrations due to weather to provide a more accurate assessment of the underlying trend in ozone caused by emissions (see https://www.epa.gov/air-trends/trends-ozone-adjusted-weather-conditions).

wages.[42] We will show that the corresponding RIAs for these alternative outcomes are precise zeros.

An important advantage of this approach is to have all those coefficients estimated in the same equation. Hence, we can straightforwardly run a test of this linear combination to obtain a coefficient and standard error for the measure of regulation-induced adaptation (RIA), and proceed with statistical inference.

Note that while in our study context we exploit daily variation in weather and monthly variation in climate norms, the empirical strategy is general and can be applied to any study context that meets the following conditions: *First*, the weather shock should be at a temporal frequency in which agents have limited opportunities to adapt, ideally at the same temporal frequency as the outcome of interest. *Second*, the climate norm should be at the temporal frequency that agents would think about climatic changes triggering adjustments that would affect the outcome of interest, and needs to be weakly longer than the weather shock. The climate norm should be lagged such that agents have time to internalize any climatic shifts and make corresponding adjustments. Recall that while the contemporaneous weather shock may affect the outcome variable through a number of potential channels, prior years' climate normal temperature can only impact the current time period's outcome variable through permanent changes, which include adaptation. *Third*, the temporal frequency of the fixed-effects must be longer than the climate norm in order to maintain variation in the norm. *Finally*, the policy or regulation of interest must have heterogeneity in its implementation across time and/or space, i.e., turning on or off across different regions or at different times periods.

Among many possible applications in, e.g., agriculture, wildfire management, or even tourism, consider the two examples of vaccine provision and law enforcement that we posed previously. For law enforcement, the outcome might be the number of dispatch calls, measured daily, or even hourly, depending on available data. The temperature shock could thus reflect the observed temperature at the same frequency, where both individuals and law enforcement may otherwise be limited in their ability to respond to temperature shocks. Meanwhile, the climate norm may reflect the norm for the respective month (lagged by, e.g., one year), corresponding to the temporal frequency at which agents may remember climate normal temperatures. The respective temporal granularity of the fixed-effects structure could thus be at the seasonal level. Finally, the policy could be, e.g., some exogenous shift in law enforcement budget, or change in legal landscape, that might affect law enforcement agencies' ability to respond to reported crimes.

Alternatively, in the context of influenza vaccine provision, the outcome may be the number of vaccines administered weekly (or monthly), while the temperature shock would reflect the average weekly (or monthly) temperature, and the norm may reflect this same, or somewhat longer, temporal frequency—lagged by 1-year. Intuitively, large decreases in temperature may trigger agents to get their yearly flu shot, and moreover agents may internalize historical seasonality in when this shift occurs, e.g., associating it with the first week of October, middle of November, or whenever would happen to correspond to their local region's climate norms. As there is typically only one flu season per year, in the winter, the fixed-effects structure might then encompass the 12-month period from July through June of the following year. Finally, the policy may be some exogenous shift in the level of

---

[42] One could also think of other pollutants such as particulate matter (PM), but as emphasized by Jacob and Winner (2009), temperature seems to play a minor role in ambient PM concentration.

vaccine provision—e.g., increasing the level of outreach, the number of individuals who are eligible, or decreasing the cost of receiving the vaccine.

5 Results

As discussed, our ultimate goal is to use Eq. (6) to recover empirical estimates of the coefficients β_N^W, β_N^C, β_A^W, and β_A^C in Eq. (7), which we can then incorporate into Eq. (5) to recover back-of-the-envelope calculations of the welfare impacts of regulation-induced adaptation under various climate scenarios. Thus, we begin by presenting our main econometric findings on the impacts of temperature on ambient ozone concentration, average adaptation, and adaptation induced by the existing NAAQS regulation under the Clean Air Act. We then discuss the robustness of our results when accounting for coinciding input regulations on ozone precursors, as well as considering the distance of ozone concentrations from the NAAQS threshold. Following this, we discuss a number of additional robustness checks regarding the measurement of climate, alternative timings for economic agents to process changes in climate and engage in adaptive behavior, and further specification checks and sample restrictions. Then, we examine heterogeneity in our recovered measure of adaptive response over time and across the temperature distribution, as well as by local (county-level) factors such as belief in climate change or precursor-limited ambient atmosphere. Finally, we map our econometric results into the analytical framework developed in Sect. 2 to estimate the welfare effects of regulation-induced adaptation due to the ozone NAAQS.

5.1 The Role of Regulations for Inducing Adaptation to Climate Change

Table 1 reports our main findings on the role of existing government regulations and policy in inducing climate adaptation. Before discussing the ozone NAAQS regulation-induced adaptation, we present the average climate impacts and adaptation across all counties in our sample. For this purpose, we run a simplified version of Eq. (6), where the temperature shock and norm are not interacted with attainment status. Column (1) shows that a 1 °C temperature shock increases average daily maximum ozone concentration by about 1.65 ppb. This can be seen as a benchmark for the ozone response to temperature because of the limited opportunities to adapt in the short run.[43] A 1 °C-increase in the 30-year MA, lagged by one year and thus revealed in the year before ozone levels are observed, increases daily maximum ozone concentration by about 1.16 ppb, an impact that is significantly lower than the response to a 1 °C temperature shock, indicating adaptive behavior by economic agents. Indeed, column (3) presents the measure of adaptation—0.49 ppb—which is economically and statistically significant. If adaptation was not taken into consideration, the impact of temperature on ambient ozone would be overestimated by roughly 42 percent.

The estimates above represent average treatment effects. Because we are interested in the role of regulations in potentially affecting adaptive behavior, we estimate heterogeneous

---

[43] We see it as a benchmark because we assume that economic agents are not able to respond to weather shocks. In reality, there might be some opportunities to make short-run adjustments in the context of ambient ozone. Although developed countries have usually not taken drastic measures to attenuate unhealthy levels of ambient ozone because concentrations are generally low, developing countries have often constrained operation of industrial plants and driving in days of extremely high levels of ozone.

treatment effects by attainment status, as specified in Eq. (6). Table 1, column (2), reports the estimates disaggregated by whether the ozone monitors are located in attainment or nonattainment counties. Given that attainment counties have cleaner air by definition, on average the ozone response to temperature changes in these counties is significantly lower than for nonattainment counties. However, as shown in column (4), adaptation in nonattainment counties is over 107 percent larger than in attainment counties. Specifically, adaptation in nonattainment counties reduces the impact of a 1 °C increase in temperature on ambient ozone concentration by 0.64 parts per billion (ppb), or about one-third of the total impact. As defined in Eq. (7), the difference between adaptation estimates in nonattainment and attainment counties—0.33 ppb—is our measure of regulation-induced adaptation, shown at the bottom of column (4), which represents just over half of the total adaptation in nonattainment counties. Therefore, a regulation put in place to correct an externality—the NAAQS for ambient ozone—generates a *co-benefit* in terms of adaptation to climate change, on top of the documented direct impact on ambient ozone concentrations (Henderson 1996).

Recall that for tractability, our analytical framework focuses mainly on climate adaptation that may be induced by the existing regulation of interest, and is agnostic about the real-world magnitude of $\frac{dE^N}{dc}$—any adaptation that is plausibly exogenous to the regulation. That is, while the framework shows that we should expect *induced* adaptation in attainment counties to be zero, that does not mean that the total level of adaptation in those counties is zero. Thus, recovering a baseline measure of "non-induced" adaptation—that which occurs in attainment counties—is a key feature of our econometric approach, allowing us to "difference-out" the adaptation in nonattainment counties that is plausibly exogenous to the NAAQS regulation.[44] Specifically, the second estimate in column (4)—0.31 ppb—indicates that adaptive behavior is in fact present in attainment counties. The underlying reasons might be technological innovation and market forces, as highlighted in previous studies (e.g., Barreca et al. 2016), other regulations affecting both attainment and nonattainment counties (e.g., Auffhammer and Kellogg 2011; Deschenes et al. 2017), or even preventive responses in counties with ozone readings near the threshold of the NAAQS for ambient ozone, as examined in our robustness checks below.

An example of adaptation triggered by innovation, market forces, and other regulations in the context of ambient ozone arises from the adoption of solar panels for electricity generation. Higher temperatures lead to more ozone formation, but they also constrain the operations of coal-fired power plants. Regulations under the Clean Water Act restrict the use of river waters to cool the boilers when water temperature rises (e.g., McCall et al. 2016). Because coal plants are important contributors of VOC and NOx emissions, those constraints lead to a reduction in the concentration of ozone precursors. At the same time, solar panels are more suitable for electricity generation in hotter areas, with higher incidence of sunlight; thus, more extensively used in those places. Now, higher temperatures combined with lower levels of ozone precursors—enabled by the adoption of solar

---

[44] One may worry that attainment and nonattainment counties could be systematically different in ways that are not fully controlled for by the included set of fixed-effects. Later, as a robustness check, we examine the results of our main specification estimated on two alternative sub-samples: one in which we include only those counties that were consistently in or out of attainment throughout the entire sample period, and another in which we instead include only those counties that switched attainment status at least once during the sample period. In both cases the results are similar to our full-sample estimates.

Table 1 Climate impacts on ambient ozone and adaptation

	Daily max ozone levels (ppb)		Implied adaptation	
	(1)	(2)	(3)	(4)
Temperature shock	1.648***			
	(0.058)			
Climate norm	1.161***		0.487***	
	(0.049)		(0.036)	
Nonattainment × Shock		1.990***		
		(0.079)		
Nonattainment × Norm		1.351***		0.639***
		(0.067)		(0.054)
Attainment × Shock		1.263***		
		(0.027)		
Attainment × Norm		0.956***		0.308***
		(0.035)		(0.029)
Regulation induced				0.332***
				(0.056)
Nonattainment control	Yes	Yes		
Precipitation controls	Yes	Yes		
Fixed effects:				
Monitor-by-season	Yes	Yes		
Region-by-season-by-year	Yes	Yes		
Observations	5,139,529	5,139,529		
R^2	0.428	0.434		

Notes: This table reports our main findings regarding the climate impacts on ambient ozone concentrations (in parts per billion—ppb) over the period 1980–2013, as well as the implied estimates of adaptation, in particular regulation-induced adaptation. Column (1) reports climate impact estimates (national average), with daily temperature decomposed into climate norms and temperature shocks. Recall that the climate norm represents a 30-year monthly moving average of temperature, lagged by 1 year, while the temperature shock reflects the daily difference between observed temperature and this norm. In column (2) we interact the climate norm and temperature shock with indicators for whether counties have been designated as in- or out- of attainment under the National Ambient Air Quality Standards (NAAQS) for ambient ozone, to estimate heterogeneous effects across attainment and nonattainment counties, as specified in Eq. (6). The attainment status is lagged by 3 years, because EPA allows at least this time period for counties to return to attainment levels. The last two columns report our adaptation estimates. By comparing the impacts of climate norm and temperature shock from column (1), we obtain our estimate of overall adaptation in column (3). Similarly, in column (4) we report the adaptation in attainment and nonattainment counties separately, which we obtain by comparing the impacts of climate norm and temperature shock reported in column (2). As defined in Eq. (7), the difference between adaptation in nonattainment and attainment counties is our measure of regulation-induced adaptation. Standard errors are clustered at the county level. ***, **, and * represent significance at 1%, 5% and 10%, respectively

panels—may lead to lower levels of ambient ozone. Hence, adaptation driven by innovation, market forces, and regulations other than the ozone NAAQS.

5.2 Robustness Checks

Parallel-trends and estimates of firm responses to climatic changes. The measure of regulation-induced adaptation (RIA) recovered by our main specification is analogous to a difference-in-differences parameter, as the difference between adaptation, which is itself the difference between the weather and climate responses, in counties designated either in attainment or nonattainment. Thus, an important condition for identifying RIA is parallel pre-trends prior to counties' nonattainment designations. We investigate this assumption via two different approaches. First, by re-estimating Eq. (6) with three alternative sample restrictions: (i) including only counties with a persistent NAAQS designation across the entire sample period—i.e., always either in attainment or nonattainment; (ii) including only counties that had their NAAQS designation switched at least one time—i.e., from attainment to nonattainment, or vice-versa; and (iii) including counties that were persistently in attainment, as well as *only* the periods of attainment for counties that were ever in nonattainment. Second, by re-estimating Eq. (6) for other county-level outcomes that capture key dimensions of local economic activity—monthly employment and quarterly wages.[45] Results reported in Table 2 correspond to the first three sample restrictions in columns (1) through (3), and the two alternative outcomes in columns (4) and (5).

Across both sub-samples reported in columns (1) and (2), the estimate of RIA is statistically indistinguishable from our full-sample estimate, suggesting that our central result is not driven by a differential response in a sub-sample of counties. Results reported in column (3) correspond to a more explicit test of pre-trends. While the ozone response to weather and climate does appear to have a *level* difference between the persistent attainment counties and the attainment periods of "ever nonattainment" counties, the estimate of regulation-induced adaptation is small in magnitude and statistically indistinguishable from zero, indicating similar pre-trends between both sets of counties.

Finally, results reported in columns (4) and (5) reveal differences between attainment and nonattainment counties with respect to both employment and wages that are precise zeros, further suggesting that the two groups of counties satisfy the parallel trends assumption. In other words, because employment and wages are not responding to the interactions of attainment status with weather and climate in the same way as ozone, the coefficients in our central specification can be reasonably interpreted as *causal moderators*—how attainment status may affect the marginal impact of weather and climate on ozone formation,[46] Furthermore, although Henderson (1996) and Becker and Henderson (2000) have shown that manufacturing plants may relocate in response to an ozone nonattainment designation, our results in Table 2 show that county-level employment and wages do not respond differentially to changes in climate across attainment and nonattainment counties, implying that our central estimate of RIA is driven by "in-place" behavioral or production adjustments, rather than permanent or transitory shifts in production location.

Estimates considering input regulation for ozone precursors. During our period of analysis (1980–2013), three other policies aiming at reducing ambient ozone concentrations were implemented in the United States: (i) regulations restricting the chemical composition of gasoline, intended to reduce VOC emissions from mobile sources (Auffhammer and Kellogg 2011), (ii) the NOx Budget Trading Program (Deschenes et al. 2017), (iii) the

---

[45] Note that while our main specification makes use of daily, monitor-level, observations, because these alternative outcomes are measured at the county level, and at a longer temporal frequency, we first construct average values of each independent variable at the county level and corresponding temporal frequency to each outcome variable of interest.

[46] Conversely, if employment or wages were responding to the interactions of attainment status with weather and climate, we would be uncovering *effect moderators* where the coefficients would be capturing both the effect of attainment/nonattainment status and any other factors that could be correlated with this status while also moderating the ozone-temperature relationship.

Regional Clean Air Incentives Market (RECLAIM) NOx and SOx emissions trading program (Fowlie et al. 2012). Notably, as these were all input regulations on ozone precursor emissions, which lack explicit climate interactions themselves, our theoretical framework suggests that they should have no impact on adaptation (see Appendix C.2 for further discussion and a proof of this extension). However, because our goal is to econometrically recover an empirical estimate of climate adaptation induced specifically by the NAAQS for ambient ozone, it is imperative to examine the sensitivity of our estimates of regulation-induced adaptation when taking into account these input regulations targeted at ozone precursors.

Table 2 Parallel Trends & Alternative Outcomes

	Only counties with persistent NAAQS status	Only counties that switched NAAQS status	Persistent attainment counties versus attainment periods of counties ever in nonattainment	Alternative outcomes	
				Employment (Log)	Wages(Log)
	(1)	(2)	(3)	(4)	(5)
Nonattainment × Shock	1.948***	1.996***	1.434***	– 0.002	0.004*
	(0.115)	(0.083)	(0.041)	(0.001)	(0.002)
Nonattainment × Norm	1.270***	1.404***	1.025***	0.002***	– 0.002
	(0.137)	(0.071)	(0.044)	(0.000)	(0.001)
Attainment × Shock	0.970***	1.444***	0.973***	– 0.000	– 0.001
	(0.027)	(0.042)	(0.027)	(0.001)	(0.001)
Attainment × Norm	0.489***	1.168***	0.490***	0.001***	– 0.000
	(0.034)	(0.046)	(0.034)	(0.000)	(0.001)
Implied adaptation					
Nonattainment	0.678***	0.593***	0.483***	– 0.000	– 0.000
	(0.098)	(0.056)	(0.034)	(0.001)	(0.002)
Attainment	0.480***	0.276***	0.409***	– 0.001	– 0.001
	(0.034)	(0.037)	(0.039)	(0.001)	(0.002)
Regulation induced	0.198*	0.317***	0.074	0.001	0.001
	(0.104)	(0.058)	(0.051)	(0.001)	(0.001)
All controls	Yes	Yes	Yes	Yes	Yes
Observations	1,122,101	4,017,428	2,455,854	84,423	28,390
R^2	0.352	0.445	0.394	0.996	0.972

Notes: This table reports the results of three alternative sample restrictions in columns (1) through (3) and two alternative outcome variables in columns (4) and (5) to examine the parallel trends assumption. Column (1) restricts the estimating sample to only include counties with a persistent NAAQS status across the entire sample period—497 attainment counties and 51 nonattainment counties. Column (2) restricts the estimating sample to only include counties that switched their NAAQS status at least once during the sample period—458 counties. The magnitudes of RIA are statistically indistinguishable from our full sample estimate, indicating that our primary results are not being driven by a sub-set of counties with specific NAAQS designations. Column (3) compares the 497 counties persistently in attainment with the periods of attainment for the 458 counties that ever switched to a nonattainment status. The estimate of RIA is statistically indistinguishable from zero, indicating that the parallel trends assumption is satisfied. Finally, columns (4) and (5) report the effects of temperature shocks and changes in the climate norm on monthly log employment and quarterly log wages at the county level for all counties in our main estimating sample, years 1990–2013. The lack of response implies that the main channel for RIA, and adaptation in general, is likely stemming from "in-place" behavioral or production adjustments, rather than, e.g., shifts in production location. The full list of controls are the same as in the main model, depicted in column (2) of Table 1. Standard errors are clustered at the county level. ***, **, and * represent significance at 1%, 5% and 10%, respectively

Auffhammer and Kellogg (2011) demonstrate that the 1980 s and 1990 s federal regulations restricting the chemical composition of gasoline, intended to curb VOC emissions, were ineffective in reducing ambient ozone concentration. Since there was flexibility regarding which VOC component to reduce, to meet federal standards refiners chose to remove compounds that were cheapest, yet not so reactive in ozone formation. Beginning in March 1996, California Air Resources Board (CARB) approved gasoline was required throughout the entire state of California. CARB gasoline targeted VOC emissions more stringently than the federal regulations. These precisely targeted, inflexible regulations requiring the removal of particularly harmful compounds from gasoline significantly improved air quality in California (Auffhammer and Kellogg 2011). Therefore, we re-estimate our analysis removing the state of California from 1996 onwards. The results reported in Table 3 reveal that the estimate for regulation-induced adaptation in column (2), derived from column (1) estimates of the impact of temperature shocks and norms on ambient ozone concentration, is remarkably close to our overall estimate of regulation-induced adaptation. Hence, it appears that VOC regulations in California do not drive our estimate of climate adaptation induced by the NAAQS for ozone, in line with our theoretical framework's predictions regarding such input regulations.

Deschenes et al. (2017) and Fowlie et al. (2012) both find a substantial decline in air pollution emissions and ambient ozone concentrations from the introduction of an emissions market for nitrogen oxides (NOx), another ozone precursor. The NOx Budget Trading Program (NBP) examined by Deschenes et al. (2017) operated a cap-and-trade system for over 2500 electricity generating units and industrial boilers in the eastern and midwestern United States between 2003 and 2008. Thus, we re-estimate our analysis excluding the states participating in the NBP, from 2003 onwards.[47] The RECLAIM NOx and SOx trading program examined by Fowlie et al. (2012) similarly operated a cap-and-trade system at 350 stationary sources of NOx for the four California counties within the South Coast Air Quality Management District (SCAQMD) starting in 1994. Thus, we again re-estimate our analysis, excluding the SCAQMD counties from 1994 onwards.[48] Table 3 reports the results excluding NBP states in columns (3) and (4), and excluding RECLAIM counties in columns (5) and (6). The estimate for regulation-induced adaptation in columns (4) and (6) are quite similar to our overall estimate of regulation-induced adaptation. Despite being effective in reducing NOx and ozone concentrations, the NBP and RECLAIM programs do not seem to affect climate adaptation induced by the NAAQS for ozone. Again, this is in line with our theoretical framework's predictions regarding such input regulations and thus not surprising.

In addition to these three policies, the CAA amendments of 1990 designated many states in the northeastern United States as part of an Ozone Transport Region (OTR). Within this region, even attainment counties were required to act to reduce emissions of NOx and VOCs (USCFR 2013). Similar to the three cases above, we re-estimate our analysis excluding the states that were designated as part of the OTR starting from 1993—when the affected states' implementation plans (SIP) had been revised to include all areas

---

[47] NBP participating states include: Alabama, Connecticut, Delaware, Illinois, Indiana, Kentucky, Maryland, Massachusetts, Michigan, Missouri, New Jersey, New York, North Carolina, Ohio, Pennsylvania, Rhode Island, South Carolina, Tennessee, Virginia, and West Virginia, and Washington, DC. The NBP operated only in northeastern states on May 1 of 2003, and expanded to the other states on May 31 of 2004 (Deschenes et al. 2017).

[48] Participating counties include: Los Angeles, Riverside, San Bernardino, and Orange.

Table 3 Accounting for Competing Input Regulations Aimed at Ambient Ozone Reductions

	VOC Regulations		NOx Regulations				VOCs and NOx	
	(Exclude California)		(Exclude NBP States)		(Exclude RECLAIM)		(Exclude OTR States)	
	Ozone (ppb)	Adaptation	Ozone (ppb)	Adaptation	Ozone (ppb)	Adaptation	Ozone (ppb)	Adaptation
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Nonattainment × Shock	2.032***		2.050***		1.987***		1.988***	
	(0.092)		(0.090)		(0.082)		(0.098)	
Nonattainment × Norm	1.370***	0.662***	1.430***	0.620***	1.320***	0.667***	1.359***	0.629***
	(0.061)	(0.064)	(0.080)	(0.062)	(0.055)	(0.061)	(0.083)	(0.066)
Attainment × Shock	1.275***		1.267***		1.263***		1.260***	
	(0.028)		(0.031)		(0.027)		(0.029)	
Attainment × Norm	0.970***	0.305***	0.978***	0.290***	0.946***	0.317***	0.968***	0.292***
	(0.034)	(0.028)	(0.041)	(0.034)	(0.033)	(0.029)	(0.039)	(0.032)
Regulation induced		0.358***		0.331***		0.349***		0.337***
		(0.065)		(0.063)		(0.062)		(0.067)
All controls	Yes		Yes		Yes		Yes	
Observations	4,631,413		4,338,183		5,008,323		4,437,345	
R^2	0.432		0.443		0.439		0.438	

Notes: This table reports results from our main specification in Eq. (6) but excluding locations with competing regulations – input regulations aimed at reducing ambient ozone concentrations via reductions in ozone precursors (VOCs and NOx). Three of these regulations were implemented in the United States over our sample period 1980–2013: (i) regulations restricting the chemical composition of gasoline, intended to reduce VOC emissions from mobile sources (Auffhammer and Kellogg 2011), (ii) the NOx Budget Trading Program (Deschenes et al. 2017), and (iii) the Regional Clean Air Incentives Market (RECLAIM) NOx and SOx emissions trading program (Fowlie et al. 2012). The CAA ammendments of 1990 also created an ozone transport region (OTR) with additional regulations on both NOx and VOC emissions for all states within the area. Because our goal is to estimate climate adaptation induced by the NAAQS for ambient ozone, here we examine the sensitivity of our estimates of regulation-induced adaptation when accounting for these input regulations. Column (1) excludes California from 1996 onwards, when stringent VOC regulations were in place. Column (3) excludes the states participating in the NBP from 2003 onwards, when the program was in effect. Column (5) excludes the four California counties within the South Coast Air Quality Management District from 1994 onwards, when the RECLAIM was in operation. Column (7) excludes all states within the OTR from 1993 onwards, when it went into effect. The implied adaptation estimates presented in columns (2), (4), (6), and (8) are derived from the estimates reported in columns (1), (3), (5), and (7) respectively. Recall that the climate norm represents a 30-year monthly moving average of temperature, lagged by 1 year, while the temperature shock reflects the daily difference between observed temperature and this norm. The full list of controls are the same as in the main model, depicted in column (2) of Table 1. Standard errors are clustered at the county level. ***, **, and * represent significance at 1%, 5% and 10%, respectively

Table 4 Results by Distance of Ozone Concentrations to NAAQS Threshold

	Nonattainment		Attainment		Induced
	Ozone (ppb)	Adaptation	Ozone (ppb)	Adaptation	Adaptation
	(1)	(2)	(3)	(4)	(5)
Panel A. Ozone (ppb) within 20% of NAAQS threshold					
Temperature shock	0.610***		0.382***		
	(0.024)		(0.014)		
Climate norm	0.539***	0.071**	0.395***	− 0.013	0.084***
	(0.033)	(0.034)	(0.017)	(0.014)	(0.029)
Sub-sample Obs			676,068		
Panel B. Ozone (ppb) within 20–40% of NAAQS threshold					
Temperature shock	0.758***		0.300***		
	(0.077)		(0.011)		
Climate norm	0.484***	0.274***	0.264***	0.036**	0.238***
	(0.061)	(0.036)	(0.025)	(0.018)	(0.043)
Sub-sample Obs			1,300,386		
Panel C. Ozone (ppb) over 40% away from NAAQS threshold					
Temperature shock	1.225***		0.772***		
	(0.123)		(0.024)		
Climate norm	0.673***	0.552***	0.479***	0.293***	0.259***
	(0.063)	(0.076)	(0.038)	(0.028)	(0.089)
Sub-sample Obs			3,162,755		
All controls			Yes		
Observations			5,139,209		
R^2			0.709		

Notes: This table reports results from our main specification in Eq. (6) including interactions with indicator variables for ozone monitor readings over the period 1980–2013 with concentrations falling within 20 percent of the NAAQS threshold in Panel (A), within 20–40 percent of the threshold in Panel (B), and over 40 percent away from the threshold in Panel (C). Note that all reported estimates for Nonattainment and Attainment counties reported in Columns (1) and (3) come from a single estimating equation. Columns (2) and (4) represent the implied measures of adaptation, while Column (5) reports the resulting measure of regulation-induced adaptation as the difference of Column (4) from column (2). Recall that the climate norm is the 30-year monthly MA of temperature lagged by 1 year, and the temperature shock is the difference between the observed temperature and the norm. The full list of controls are the same as in the main model, depicted in column (2) of Table 1. For reference, the 1979 NAAQS for designating a county's attainment status was based on an observed 1-hour maximum ambient ozone concentration of 120 ppb or higher, while the 1997 amendment (implemented in 2004 due to lawsuits) changed this to an observed maximum 8-hour average ambient ozone concentration of 80 ppb or higher, and the 2008 update further reduced this to 75 ppb. Standard errors are clustered at the county level. ***, **, and * represent significance at 1%, 5% and 10%, respectively

in the OTR.[49] Table 3 reports the results excluding OTR states in columns (7) and (8).

---

[49] Affected states include: Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, and the Consolidated Metropolitan Statistical Area that includes the District of Columbia. For the latter, we include both DC and the entire state of Virginia, as the amended SIP may have affected statewide policy.

The estimate for regulation-induced adaptation in column (8) are once again quite similar to our overall estimate of regulation-induced adaptation amd in line with our theoretical framework's predictions regarding such input regulations. These estimates have the added benefit of addressing a separate potential concern: cross-county adaptation spillovers. Theoretically, adaptation efforts in a nonattainment county could reduce the pollution in a neighboring attainment county. This would imply a higher level of adaptation in the attainment county than occurred, leading to a downward bias in the estimate of RIA. This potential concern would be most pronounced in areas where pollution is likely to transport across county boundaries—for example, in the OTR. As we find no statistically significant difference between our central estimate of RIA and the estimate when excluding OTR states, this suggests that cross-county spillover effects, should they exist, are not of meaningful magnitude.

Estimates by distance of ozone concentrations to NAAQS threshold. One may ponder that the ideal setting to identify regulation-induced adaptation would be to randomly assign regulation, and compare the impact of climatic changes in regulated versus unregulated jurisdictions. Nevertheless, this would work only if the regulation was unanticipated and imposed only once. If regulations are anticipated, and can be assigned multiple times, in multiple rounds, such as the Clean Air Act nonattainment designations, economic agents may respond more similarly to the threat of regulation, even when it is randomly assigned. They might be indifferent between making adjustments before or after being affected by the regulation if more rounds of regulatory action are on the horizon. The intuition for these results is similar to the outcomes of finitely versus infinitely repeated games (or games that are being repeated an unknown number of times). Consider the prisoner's dilemma game. If played a finite number of times, defection may yield higher payoffs, following familiar backward-induction arguments. But if played an infinite (or an unknown) number of times, cooperation may emerge as a preferable outcome.

In the case of the Clean Air Act, EPA designates counties out of compliance with NAAQS if their pollution concentrations are above a known threshold. Such designations may change over time depending on the adjustments made by economic agents in those jurisdictions. For counties whose pollution concentration is around the threshold, economic agents may have incentives to make efforts to comply with NAAQS no matter whether those counties are just above or just below the threshold. If counties are even a little above the standards, EPA mandates them to adopt emissions control technologies and practices to reduce pollution, which is costly. If counties are a little under the standards, they may want to keep it that way to avoid regulatory oversight. As a result, they may end up making efforts to maintain the area under attainment. This somewhat similar adaptive behavior around the ozone standards may reduce the estimates for regulation-induced adaptation near the NAAQS threshold.[50]

Table 4 reports estimates recovered by interacting our main specification with monitor-level indicators for whether the daily ozone concentration fell within 20 percent, above or below, the NAAQS threshold in Panel A, between 20 and 40 percent away from the

---

[50] It is important to mention that before the 1990 CAA amendments, EPA used a "too close to call" nonattainment category with minimal requirements for areas just violating the NAAQS. Areas in this category (with ozone levels up to 138 ppb, hence above the threshold of 120 ppb) were not subject to full SIP requirements, but rather watched closely to see if their air quality was getting worse (Krupnick and Farrell 1996). This malleability in enforcement may also reduce the estimate for regulation-induced adaptation near the NAAQS threshold.

Table 5 Implied Impacts of Ambient Ozone Climate Penalty

	Nonattainment counties				
	1 °C increase	RCP 4.5 scenario		RCP 8.5 scenario	
		2050	2100	2050	2100
	(1)	(2)	(3)	(4)	(5)
Costs (Millions 2015 USD/year)					
Without adaptation	1766	2473	4946	2826	8479
With adaptation	1199	1679	3357	1918	5755
Savings (Millions 2015 USD/year)					
From adaptation	567	794	1589	908	2723
Regulation induced adaptation	294	412	824	471	1412
Net RIA welfare co-benefit	196	275	549	314	940

Notes: This table reports some back-of-the-envelope calculations on a class of *co-benefits* of the existing Clean Air Act regulations—climate adaptation induced by the NAAQS for ambient ozone. The calculations are derived from the main estimates in Table 1 and the costs associated with those climate penalties on ambient ozone in the United States, for all 509 counties ever in nonattainment in our sample, under a variety of climate scenarios. The social costs of ozone increases are inferred from the estimated willingness to pay (WTP) for a 1 ppb decrease in the mean 8-hour summer ozone concentration in the states participating in the U.S. NOx Budget Program—about \$1.7 million (2015 USD) per county per year (Deschenes et al. 2017, p. 2985, Table 6, Panel D, Column 5). Column (1) reports the impacts of a 1 °Celsius increase in temperature as a baseline effect, while columns (2) and (3) extend these effects to match the expected temperature increases under the Representative Concentration Pathway (RCP) 4.5 climate scenario at mid- and late- century. Similarly, columns (4) and (5) extend the effects out to mid- and late- century under the more damaging RCP 8.5 climate scenario. Temperature projections are based on global models and downscaled products from CMIP5 (Coupled Model Intercomparison Project Phase 5) using a suite of RCPs. The annual average temperature of the contiguous United States is projected to rise throughout the century. Increases for the period 2021–2050 relative to 1976–2005 are projected to be about 1.4 °C (2.5 °F) for a lower scenario (RCP4.5) and 1.6 °C (2.9 °F) for the higher scenario (RCP 8.5). In other words, recent record-breaking years may be “common” in the next few decades. By late-century (2071–2100), the RCPs diverge significantly, leading to different rates of warming: approximately 2.8 °C (5.0 °F) for RCP4.5, and 4.8 °C (8.7 °F) for RCP 8.5 (Vose et al. 2017, p. 195). In this table, the first row reports the expected effect of the relevant temperature increase by using the estimate of temperature shock from column (2) of Table 1. The second row then reports what these impacts would be after including adaptation by instead using the estimate of climate norm from the same column of Table 1. Row three displays the implied savings, simply reflecting the difference between the first two rows. Further, by taking the difference between the measures of adaptation in nonattainment and attainment counties from Table 1, column (4), row four reports the component of these savings that can be attributed to adaptation induced by the NAAQS for ambient ozone, which we termed regulation-induced adaptation. Finally, row 5 accounts for the fact that adaptation is unlikely to be costless. Using the EPA’s estimate of the cost of reducing the ozone NAAQS by 1 ppb—\$296 million per year (USEPA 2015a)—multiplied by the 0.332 ppb value of RIA, implies a cost of RIA of \$98 million per year per 1°C. Subtracting this value, scaled corresponding to each respective column, from the *gross* welfare benefits reported in row 4 gives an approximate estimate of the *net* welfare co-benefits of adaptation induced by the NAAQS regulation

threshold in Panel B, and over 40 percent away from the threshold in Panel C.[51] The

---

[51] Recall that the EPA changed the criteria for designating a county out of attainment in 1997 (implemented in 2004 after litigation) and again in 2008 to use the 4th highest 8-hour concentration level—80 ppb and 75 ppb respectively—rather than the 1st highest 1-hour concentration level of 120 ppb. In our analysis we compare the 1st highest 1-hour concentration level, our outcome of interest, against the prevailing NAAQS threshold for constructing these daily indicators. As noted by the EPA, the 4th highest 8-hour concentration of 80 ppb should approximate the 1st highest 1-hour concentration level of 120 ppb. Thus in unreported analyses we also consider estimates where we use only the 1-hour 120 ppb threshold in con-

observations within 20 percent of the NAAQS threshold comprise about 13 percent of the overall sample. As expected, the empirical evidence we provide for this subset indicates limited differential adaptation across attainment and nonattainment counties, but still of nontrivial magnitude. The estimate for regulation-induced adaptation, which is the difference between the adaptation estimates in columns (2) and (4), is still economically and statistically significant.

For the observations of ambient ozone concentration within 20–40 percent of the NAAQS threshold (25 percent of the overall sample), and over 40 percent away from the threshold (62 percent of the overall sample), we cannot rule out that the estimates of regulation-induced adaptation reported in column (5) are similar to our main estimate. Given that together these observations make up 87 percent of the overall sample, it is fair to say that most of the regulation-induced adaptation arises from monitors with ozone readings relatively far from the NAAQS threshold.

Other robustness checks and sample restrictions. We further examine the sensitivity of our results to a host of additional robustness checks in Appendix B. Table B1 examines the choice of a 3-year lag on counties' nonattainment status, as the EPA may give some counties a longer deadline to reach compliance. Conversely, a 3-year lag implicitly assumes that counties which had re-entered attainment status would continue to act as if they were in nonattainment for the first few years. We re-estimate Eq. (6) using a 1-year and a 6-year lag on the nonattainment indicator, finding results that are economically and statistically similar to our central results, suggesting that the choice of the 3-year lag does not meaningfully impact our estimates.

Table B2 varies our moving average measure of climate to investigate whether measurement error may be of concern, potentially arising from our decomposition of meteorological variables using a 30-year MA. Alternatively, there may be concern with our choice of a 1-year lagged 30-year MA in our preferred specification, implying that agents adapt within one year—or the assumption that agents are constrained to adapt in the short-run. To investigate the first concern we repeat our analysis using a 10-year and 20-year lag in place of the 1-year lag, with results presented in columns (1) and (2) of Table B3.[52] To address the second concern we make use of a widespread "Ozone Action Day" alert policy, whereby the local air pollution authority would release a public alert, typically a day or two in advance, that meteorological conditions are expected to be especially conducive to ozone formation. To the extent that agents are adapting to contemporaneous weather shocks, we would be most likely to observe an adaptive response on these high impact days, especially considering the prior warning. Table B4 explores further specification checks—using a *daily* rather than monthly MA, or including other meteorological controls, and sample restrictions—constraining the estimating sample to a semi-balanced panel.

Furthermore, we provide results using a variety of alternative matching rules between ozone monitors and weather stations in Table B5: varying the distance cut-off, the number of monitors in the matching, and the averaging procedure. Estimates in all of the above

---

Footnote 51 (continued)

structing the indicator variables, and estimates where we use only the observations prior to the NAAQS change in 2004. In both cases results are qualitatively similar to our preferred specification reported in Table 4.

[52] Note that NOAA weather data only has nationwide coverage available from approximately 1950 onwards. Thus, when using a 10-year lag the MA is comprised of only 20 years, while with the 20-year lag the MA consists of only 10 years.

analyses are relatively stable across the alternative approaches. Lastly, recall that our standard errors are clustered at the county level. Since the 30-year MAs and temperature shocks could be considered generated regressors, we also provide standard errors block bootstrapped at the county level for our main estimates in Appendix Table B6. Bootstrapped standard errors are all within 6% of those estimated via clustering at the county level. Because the changes were usually relatively minor, for simplicity we use clustered standard errors at the county level in the remainder of the analyses.[53]

5.3 Heterogeneity in Regulation-Induced Adaptation

Once we have recovered a measure of regulation-induced adaptation from the differential responses to weather shocks and longer-term climatic changes in nonattainment and attainment counties, we are then able to explore heterogeneity in the degree of adaptation across other dimensions. Specifically, we examine heterogeneity along four dimensions: across time and the temperature distribution, as well as by local belief in climate change and local atmospheric composition.

Adaptation across time and temperature. So far we have demonstrated that existing government regulations and policy can be effective in inducing climate adaptation. Now, we examine these estimates by decade. As reported in Appendix Table B7, the magnitude of regulation-induced adaptation in the 1980's is marginally larger, declining somewhat in the 1990's, and further still in the 2000's—for all three decades, however, estimates of regulation-induced adaptation are not statistically different from our central result. Looking at the recovered coefficients for β^W and β^C specifically, however, reveals an interesting trend. The ozone-temperature gradient itself declines meaningfully over time in both attainment and nonattainment counties, in line with what one might expect from previous studies suggesting that the CAA may induce innovation and diffusion of pollution abatement technologies (e.g., Popp 2003, 2006). To that extent, our results—which focus on the static adaptation induced by the NAAQS—may present a lower-bound of the total adaptation induced by the CAA which may also have dynamic elements.

Examining the estimates across the temperature distribution in Tables B8a and B8b, RIA ranges between 0.182 ppb to 0.268 ppb for the three temperature bins below 30 °C, approximately doubling to 0.452 ppb in the 30–35 °C bin, and almost tripling to 0.689 ppb when above 35 °C—in line with the idea that nonattainment counties may especially focus adaptive efforts on months with the hottest days, when they would otherwise have been most likely to exceed the NAAQS threshold.

Adaptation by local climate beliefs and local atmospheric composition. While the above analyses examine heterogeneity in adaptive response across time and the temperature distribution, one may wonder how adaptation varies across other dimensions, i.e., spatially, such as between areas with different climate beliefs or different underlying atmospheric conditions. In the absence of direct climate policy at the national and international stage, action driven by local culture may help address the challenge of climate change (Stavins et al. 2014). At the same time, the underlying composition of precursor emissions in the local atmosphere may also play an important role.

---

[53] Appendix Table B6 also reports standard errors clustered at the state level and two-way clustered by county and week. The estimated standard error for RIA increases by up to 39%, but the coefficient remains statistically significant at the 1% level.

Table B9 in Appendix B.2 examines this first point, using the results of a relatively recent county-level survey regarding residents' beliefs in climate change (Howe et al. 2015).[54] We create county-level indicators for terciles of high, medium, and low belief, and interact the indicators for high- and low-belief counties with our temperature and control variables, taking the median-belief tercile of counties as the baseline.[55] Our results suggest that climate beliefs may significantly affect the level and *channel* of regulation-induced adaptation: high-belief counties are associated with approximately 45% higher adaptation when in nonattainment, but are no different from baseline counties when in attainment; conversely, low-belief counties are associated with approximately 44% lower adaptation when in attainment, but maintain a similar level of adaptation as baseline counties when in nonattainment.[56] This could be due to, e.g., low-belief counties only engaging in adaptive behavior when forced to do so, i.e., when designated as in nonattainment, while conversely, high-belief counties may take a nonattainment designation as a call to action, engaging in greater levels of adaptation than may otherwise be necessary if simply trying to meet the NAAQS requirements for ozone concentration levels.

Similarly, Table B12 in Appendix B.2 examines the second point. Due to the Leontief-like production function of ozone, counties may find themselves with an atmospheric composition that is "limited" in either precursor component—VOCs or NOx. We create county-level indicators, at 5-year intervals, for whether a county is, in general, VOC- or NOx-limited and interact these indicators with our temperature and control variables, taking the counties with non-limited atmosphere as the baseline.[57] Our results suggest that while counties without a precursor-limited atmosphere still observe regulation-induced adaptation, the effect is almost quadrupled in VOC-limited counties and doubled in NOx-limited counties, though the latter is statistically imprecise. This result is perhaps unsurprising. Areas which have a local atmosphere that is already limited with regards to one of the precursors may be able to focus their efforts on continuing to reduce the limiting pollutant, which would likely have a larger impact on ozone formation than similar efforts in areas where neither NOx nor VOCs are a limiting factor.

---

[54] Specifically, Howe et al. (2015) develop a modelling technique to estimate local climate beliefs at a high degree of granularity using less granular survey results in combination with demographic characteristics. Their model results are externally validated against independently conducted surveys and are found to have an average margin of error of ± 8% at the county level using bootstrap and a 95% confidence interval. In either case, as we only have cross-sectional variation in beliefs, which may be correlated with other demographic and local characteristics, we interpret these results as suggestive of an effect moderator, rather than a causal moderator, on the magnitude of RIA caused by the ozone NAAQS.

[55] Appendix Figure A10 depicts the evolution of ozone concentration for these three sets of counties from 1980–2013. While the pattern for low- and median-belief counties track quite similarly, high-belief counties began with higher ozone concentrations, on average, but have now mostly converged with the other counties. Additionally, Table B10 provides summary statistics of basic demographic characteristics across these three county groupings using data from the 2006–2010 5-year American Community Survey.

[56] As a placebo check on these findings, we also examine the heterogeneity in our results when separating counties into low- median- and high-belief regarding "preferences" for single-parenthood in Table B11.

[57] Following the scientific literature, observations with a ratio of VOCs to NOx less than or equal to 4 are coded as VOC-limited, while those greater than 15 are coded NOx-limited, and the remainder are coded as non-limited.

5.4 Climate Adaptation Co-benefits from Existing Regulations: Some Calculations

Having presented our main findings, we now provide some back-of-the-envelope calculations on the *co-benefits* of the existing Clean Air Act associated with climate adaptation induced by the NAAQS for ambient ozone. Following the sufficient statistic approach (Harberger 1964; Chetty 2009; Kleven, forthcoming) as outlined in Sect. 2, these calculations combine our main estimates from Table 1 with climate projections from the U.S. Fourth National Climate Assessment (Vose et al. 2017), and the social benefits of ozone reductions from Deschenes et al. (2017). As detailed in Eq. (7), all of these elements can be mapped directly into the components of Eq. (5), allowing us to interpret the resulting values as welfare changes. Additionally, we also discuss how these co-benefits are affected by the projected changes in climate over the 21st century.

Formally, we map each of these three "sufficient statistics" to the components of Eq. (5), summing across every county n in the set of counties ever designated as nonattainment (NA) within our sample period:

$$\frac{1}{\lambda}\frac{\Delta V}{\Delta c} \approx -\sum\nolimits_{n\in NA} \underbrace{\frac{\phi'}{\lambda}}_{DGS} \underbrace{\frac{dE}{dc}_{n}}_{Table 1} \underbrace{\Delta c_n}_{Vose}, \tag{8}$$

where $\frac{\phi'}{\lambda}$ is treated as a fixed value, approximately equal to \$1.75 million (2015 US) per county per year, following Deschenes et al. (2017). The value of Δc varies depending on the chosen climate projection from Vose et al. (2017), while $\frac{dE}{dc}$ varies depending on whether, and which type, of adaptation is being calculated, following directly from our central results in columns (2) and (4) of Table 1.

Table 5 presents the costs of climate change, the savings from overall adaptation, and particularly the savings from regulation-induced adaptation—the co-benefit of the ozone NAAQS. We focus on the 509 counties most affected by the NAAQS for ambient ozone (nonattainment counties), representing about two thirds of the U.S. population. The row labeled costs "without adaptation" uses the estimated effects of temperature shocks on ambient ozone—β_N^W—and the one labeled "with adaptation" uses the estimated impacts of changes in climate norms (lagged 30-year MAs)—β_N^C. These are the main results reported in Table 1—the estimated coefficients for nonattainment counties from column (2). In addition, the row labeled savings "from adaptation" report the difference between the costs with and without adaptation—$\left(\beta_N^W - \beta_N^C\right)$—and the row labeled "regulation-induced adaptation" displays the portion of the adaptation due to the NAAQS for ambient ozone—*RIA* as in Eq. (7).

Table 5, column (1), reports the costs associated with increased ambient ozone, and potential savings from adaptation, from a 1 °C increase in temperature—i.e., $\Delta c = 1$. The costs arising from additional ambient ozone amount to approximately \$1.77 billion (2015 USD) per year when we use the benchmark effect of temperature shocks that do not take into account adaptation. They reduce to approximately \$1.2 billion using the impact of changes in climate norms, which does incorporate adaptive behavior. The difference of \$567 million per year is the total potential savings from adaptation, 52 percent of which is induced by the NAAQS for ambient ozone. The portion induced by the NAAQS represents the co-benefits of the Clean Air Act in terms of climate adaptation, and can be interpreted as additional societal welfare gains from that existing regulation, as informed by Eq. (5). In the next four columns, all estimates are scaled up with the temperature projections from Vose et al. (2017)—e.g., $\Delta c = 1.4$ in column (2). Regulation-induced adaptation, in particular, reaches the range of $412–471 million per year by mid-century, and $824–1,412 million by the end of the century.

Adaptation, however, is typically not costless and the above estimates in Table 5 reflect the *gross* annual co-benefits of (regulation-induced) adaptation. Using the EPA's estimated cost of strengthening the current NAAQS by 1 ppb, $296 million per year USEPA (2015b), multiplied by 1/3 to reflect the 0.332 ppb reduction per 1 °C arising from RIA, suggests that RIA is associated with an approximate annual cost of $98 million. Thus, the *net* adaptation co-benefits of the ozone NAAQS are approximately $196 million per year per 1 °C, or approximately $275–314 annually by mid-century, depending on warming scenario. These are nontrivial additional welfare gains brought about by the air quality standards regarding ambient ozone.

6 Concluding Remarks

Understanding whether and how we can adapt to a changing climate is essential for individuals and policymakers seeking to develop efficient climate policies. Faced with the political challenges of creating new, first-best climate policies, the urgency to address climate change, and the often slow pace and distributional implications of market-based adaptation, it may be relatively easier in the short-run to adjust existing policy to maximize adaptation co-benefits while working towards comprehensive climate policy.

This study develops an analytical framework and presents the first credible estimates of regulation-induced adaptation. We develop an analytical framework to examine the interactions between climate change and existing corrective policy or regulations established for reasons unrelated to climate change, revealing that when climate change would exacerbate a market failure the existing regulation or policy would trigger an adaptive response, reducing climate impacts. We then demonstrate this induced adaptation effect empirically, examining the impact of temperature changes on ambient ozone concentration in the United States from 1980–2013. Comparing the adaptive response to long-run climatic changes in temperature between counties in or out of attainment with the Clean Air Act's National Ambient Air Quality Standard for ambient ozone reveals an adaptive response that is more than twice as large in nonattainment counties. This regulation-induced adaptation in nonattainment counties has non-trivial welfare effects, implying an additional co-benefit of the ozone NAAQS of up to $412–471 million per year by mid-century—or approximately 5–10% of the EPA's estimated range of direct health benefits of the ozone NAAQS (USEPA 2015b).

The NAAQS for ozone is an ideal setting for examining regulation-induced adaptation, both because of its direct policy relevance and because climate change is expected to increase ozone concentrations in the near future. Thus, by highlighting an additional benefit of the NAAQS that had previously been unaccounted for, our findings may contribute to the design or revision of pollution control policy as well. However, while this analysis focuses on ozone as one instance of regulation-induced adaptation, the proposed concept and methodological approach are general and could be applied to examine a broad class of existing non-climate corrective policies with potential climate interactions.[58] For example,

---

[58] Notably, these potential adaptation co-benefits are *in addition* to the intended direct effects of the government policies, regulations, or provision of public goods. For example, Dell et al. (2014) note that snowfalls that occasionally disrupts Southern U.S. states have negligible effects in the Northeast, in part because of policy-induced investments in snow removal.

law enforcement and the military may additionally act as buffers against climate-related crime and conflict; vaccination campaigns, such as with influenza, may additionally help to cope with more severe influenza seasons that are likely to emerge with global warming (Towers et al. 2013). Importantly, while our empirical analysis makes use of daily data and compares within-season monthly climate normals to identify the climate impact, this is not a necessary requirement of the underlying method. For example, in the context of agriculture or vaccine provision, the appropriate temporal frequency of the climate norm may be longer, such as the within-year growing season or flu season. The method is flexible, allowing the researcher to adjust the parameters of the estimating equation to their specific study context's outcome of interest and period of analysis.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10640-023-00793-3. The replication package is available at https://doi.org/10.3886/E192847V1.

Funding Open Access funding provided by Carnegie Mellon University.

References

Acemoglu D, Shimer R (1999) Efficient unemployment insurance. J Political Econ 107(5):893–928

Aldy JE, Zeckhauser RJ (2020) Three prongs for prudent climate policy. NBER Working Paper #26991

Aldy JE, Auffhammer M, Cropper ML, Fraas AG, Morgenstern R (2020) Looking back at fifty years of the clean air act. NBER Working Paper #26687

Annan F, Schlenker W (2015) Federal crop insurance and the disincentive to adapt to extreme heat. Am Econ Rev: Papers Proc 105(5):262–66

Auffhammer M (2018) Climate adaptive response estimation: short and long run impacts of climate change on residential electricity and natural gas consumption using big data. NBER Working Paper #24397

Auffhammer M, Kellogg R (2011) Clearing the air? The effects of gasoline content regulation on air quality. Am Econ Rev 101(6):2687–2722

Barreca A, Clay K, Deschenes O, Greenstone M, Shapiro JS (2016) Adapting to climate change: the remarkable decline in the US temperature-mortality relationship over the twentieth century. J Polit Econ 124(1):105–159

Becker R, Henderson V (2000) Effects of air quality regulations on polluting industries. J Polit Econ 108(2):379–421

Bento A, Kaffine D, Roth K, Zaragoza-Watkins M (2014) The effects of regulation in the presence of multiple unpriced externalities: evidence from the transportation sector. Am Econ J Econ Pol 6(3):1–29

Bento A, Miller N, Mookerjee M, Severnini E (2023) A unifying approach to measuring climate change impacts and adaptation. Journal of Environmental Economics and Management, forthcoming

Bovenberg AL, Goulder LH (1996) Optimal environmental taxation in the presence of other taxes: general-equilibrium analyses. Am Econ Rev 86(4):985–1000

Carleton T, Delgado M, Greenstone M, Houser T, Hsiang S, Hultgren A, Jina A, Kopp R, McCusker K, Nath I, Rising J, Rode A, Seo HK, Simcock J, Viaene A, Yuan J, Zhang A (2019) Valuing the global mortality consequences of climate change accounting for adaptation costs and benefits. University of Chicago Becker Friedman Institute Working Paper No. 2018-51

Chay KY, Greenstone M (2005) Does air quality matter? Evidence from the housing market. J Polit Econ 113(2):376–424

Chetty R (2009) Sufficient statistics for welfare analysis: a bridge between structural and reduced-form methods. Annu Rev Econ 1:451–488

Dell M, Jones BF, Olken BA (2014) What do we learn from the weather? The new climate-economy literature. J Econ Lit 52(3):740–798

Deschenes O, Greenstone M (2007) The economic impacts of climate change: evidence from agricultural output and random fluctuations in weather. Am Econ Rev 97(1):354–85

Deschenes O, Greenstone M (2011) Climate change, mortality, and adaptation: evidence from annual fluctuations in weather in the US. Am Econ J Appl Econ 3(4):152–85

Deschenes O, Greenstone M, Shapiro JS (2017) Defensive investments and the demand for air quality: evidence from the NOx budget program. Am Econ Rev 107(10):2958–89

Doyle JJ Jr (2005) Health insurance, treatment and outcomes: using auto accidents as health shocks. Rev Econ Stat 87(2):256–270

Fowlie M, Holland SP, Mansur ET (2012) What do emissions markets deliver and to whom? Evidence from Southern California's NOx trading program. Am Econ Rev 102(2):965–993

Frisch R, Waugh FV (1933) Partial time regressions as compared with individual trends. Econometrica 1(4):387–401

Gibson M (2019) Regulation-induced pollution substitution. Rev Econ Stat 101(5):827–840

Goulder LH (2020) Timing is everything: how economists can better address the urgency of stronger climate policy. Rev Environ Econ Policy 14(1):143–156

Goulder LH, Parry IWH (2008) Instrument choice in environmental policy. Rev Environ Econ Policy 2(2):152–174

Goulder LH, Parry IWH, Williams RC III, Burtraw D (1999) The cost-effectiveness of alternative instruments for environmental protection in a second-best setting. J Public Econ 72(3):329–360

Grainger C, Schreiber A, Chang W (2019) Do regulators strategically avoid pollution hotspots when siting monitors? Evidence from remote sensing of air pollution. Mimeo

Greenstone M (2002) The impacts of environmental regulations on industrial activity: evidence from the 1970 and 1977 clean air act amendments and the census of manufactures. J Polit Econ 110(6):1175–1219

Harberger AC (1964) The measurement of waste. Am Econ Rev Papers Proc 54(3):58–76

Henderson JV (1996) Effects of air quality regulation. Am Econ Rev 86(4):789–813

Heutel G, Miller NH, Molitor D (forthcoming) Adaptation and the mortality effects of temperature across U.S. climate regions. Rev Econ Stat

Howe PD, Mildenberger M, Marlon JR, Leiserowitz A (2015) Geographic variation in opinions on climate change at state and local scales in the USA. Nat Clim Chang 5(6):596–603

Hsiang SM, Burke M, Miguel E (2013) Quantifying the influence of climate on human conflict. Science 341(6151):1235367

Hsu JW, Matsa DA, Melzer BT (2018) Unemployment insurance as a housing market stabilizer. Am Econ Rev 108(1):49–81

IPCC Intergovernmental Panel on Climate Change (2021) Summary for policymakers. In: Climate change 2021: the physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. , ed. Masson DV, Zhai P, Pirani A, Connors SL, Péan C, Berger S, Caud N, Chen Y, Goldfarb L, Gomis MI, Huang M, Leitzell K, Lonnoy E, Matthews JBR, Maycock TK, Waterfield T, Yelekçi O, Yu R, Zhou B. Cambridge, United Kingdom and New York, NY:Cambridge University Press

IPCC Intergovernmental Panel on Climate Change (2022) Summary for policymakers. In: Climate change 2022: impacts, adaptation and vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. , ed. Pörtner H-O, Roberts DC, Tignor M, Poloczanska ES, Mintenbeck K, Alegría A, Craig M, Langsdorf S, Löshke S, Möller V, Okem A, Rama B. Cambridge, United Kingdom and New York, Cambridge University Press, NY

Jacob DJ, Winner DA (2009) Effect of climate change on air quality. Atmos Environ 43(1):51–63

Kleven, Henrik J (forthcoming)Sufficient statistics revisited. Annu Rev Econ

Kousky C (2012) Informing climate adaptation: a review of the economic costs of natural disasters, their determinants, and risk reduction options. Resources for the Future Discussion Paper, 12–28

Krupnick AJ, Farrell D (1996) Six steps to a healthier ambient ozone policy. Resources for the Future Discussion Paper, 96-13

Lipsey RG, Lancaster K (1956) The general theory of second best. Rev Econ Stud 24(1):11–32

Lovell MC (1963) Seasonal adjustment of economic time series and multiple regression analysis. J Am Stat Assoc 58(304):993–1010

Lucas RE Jr (1976) Econometric policy evaluation: a critique. Carn-Roch Conf Ser Public Policy 1:19–46

Marcus M, Sant'Anna PHC (2021) The role of parallel trends in event study settings: an application to environmental economics. J Assoc Environ Resour Econ 8(2):235–275

McCall J, Macknick J, Hillman D (2016) Water-related power plant curtailments: an overview of incidents and contributing factors. National Renewable Energy Laboratory (NREL) Technical Report NREL/TP-6A20-67084

McGrath JM, Betzelberger AM, Wang S, Shook E, Zhu X-G, Long SP, Ainsworth EA (2015) An analysis of ozone damage to historical maize and soybean yields in the United States. Proc Natl Acad Sci 112(46):14390–14395

Michel-Kerjan EO (2010) Catastrophe economics: the national flood insurance program. J Econ Perspect 24(4):165–86

Moretti E, Neidell M (2011) Pollution, health, and avoidance behavior: evidence from the ports of Los Angeles. J Human Resour 46(1):154–75

Mukherjee A, Sanders NJ (2021) The causal effect of heat on violence: social implications of unmitigated heat among the incarcerated. National Bureau of Economic Research

Muller NZ, Ruud PA (2018) What forces dictate the design of pollution monitoring networks? Environ Model Assess 23(1):1–14

Mullins JT, White C (2020) Can access to health care mitigate the effects of temperature on mortality? J Public Econ 191:104259

Neidell M (2009) Information, avoidance behavior, and health: the effect of ozone on asthma hospitalizations. J Human Resour 44(2):450–78

NOAA National Oceanic & Atmospheric Administration (2014) National Oceanic and Atmospheric Administration (NOAA), global historical climatology network. ftp://ftp.ncdc.noaa.gov/pub/data/ghcn/daily/by_year/, accessed on November 30, 2014

Nordhaus W (2019) Climate change: the ultimate challenge for economics. Am Econ Rev 109(6):1991–2014

Popp D (2003) Pollution control innovations and the Clean Air Act of 1990. J Policy Anal Manage 22(4):641–660

Popp D (2006) International innovation and diffusion of air pollution control technologies: the effects of NOX and SO2 regulation in the US, Japan, and Germany. J Environ Econ Manag 51(1):46–71

Ranson M (2014) Crime, weather, and climate change. J Environ Econ Manag 67(3):274–302

Schlenker W, Roberts MJ (2009) Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. Proc Natl Acad Sci 106(37):15594–98

Sillman S, He D (2002) Some theoretical results concerning O3-NOx-VOC chemistry and NOx-VOC indicators. J Geophys Res Atmos, 107(D22): 26–1–26–15

Solon G (1992) Intergenerational income mobility in the United States. Am Econ Rev 82(3):393–408

Stavins R, Zou J, Brewer T, Conte GM, den Elzen M, Finus M, Gupta J, Hohne N, Lee M-K, Michaelowa A, Paterson M, Ramakrishna K, Wen G, Wiener J, Winkler H (2014) International cooperation: agreements and instruments. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change., ed. Edenhofer O, Pichs-Madruga R, Sokona Y, Farahani E, Kadner S, Seyboth K, Adler A, Baum I, Brunner S, Eickemeier P, Kriemann B, Savolainen J, Schlömer S, von Stechow C, Zwickel T, Minx JC. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, Chapter 13:1001–1082

Towers S, Chowell G, Hameed R, Jastrebski M, Khan M, Meeks J, Mubayi A, Harris G (2013) Climate change and influenza: the likelihood of early and severe influenza seasons following warmer than average winters. PLoS Currents Influenza, 5: ecurrents.flu.3679b56a3a5313dc7c043fb944c6f138

USCFR U.S. Code of Federal Regulations (2013) National archives and records administration, federal register, Title 42 Public Health, Chapter 85, Subchapter 1, Part D, Subpart 2, Sec. 7511c

USEPA U.S. Environmental Protection Agency (1979) Revisions to the national ambient air quality standards for photochemical oxidants: final rulemaking. Federal Register, 44(28): 8202–8237. February 8, 1979

USEPA U.S. Environmental Protection Agency (1997) National ambient air quality standards for ozone: final rule. Federal Register, 62(138): 38856–38896. July 18, 1997

USEPA U.S. Environmental Protection Agency. (2004) Final rule to implement the 8-hour ozone national ambient air quality standard—Phase 1. Federal Register, 69(84): 23951–24000. April 30, 2004

USEPA U.S. Environmental Protection Agency (2008) National ambient air quality standards for ozone: final rule. Federal Register, 73(60): 16435–16514. March 27, 2008

USEPA U.S. Environmental Protection Agency (2015a) National ambient air quality standards for ozone: final rule. Federal Register, 80(206): 65291–65468. October 26, 2015

USEPA U.S. Environmental Protection Agency (2015b) Regulatory impact analysis of the final revisions to the national ambient air quality standards for ground-level ozone. Washington, DC: U.S.

Environmental Protection Agency, Office of Air and Radiation and Office of Air Quality Planning and Standards, EPA-452/R-15-007

Vose RS, Easterling DR, Kunkel KE, LeGrande AN, Wehner MF (2017) Temperature changes in the United States. In: Climate Science Special Report: Fourth National Climate Assessment, Volume I. , ed. Wuebbles DJ, Fahey DW, Hibbard KA, Dokken DJ, Stewart BC, and Maycock TK, Chapter 6, pp 185–206. Washington, DC:U.S. Global Change Research Program

White C (2021) Measuring social and externality benefits of influenza vaccination. J Human Resour 56(3):749–785

WMO (2017) WMO guidelines on the calculation of climate normals. World Meteorological Organization Geneva, Switzerland

Zivin JG, Neidell M (2012) The impact of pollution on worker productivity. Am Econ Rev 102(7):3652–3673

Authors and Affiliations

Antonio M. Bento[1,2] **· Noah Miller**[1] **· Mehreen Mookerjee**[3] **· Edson Severnini**[4,2,5]

✉ Edson Severnini
edsons@andrew.cmu.edu

Antonio M. Bento
abento@usc.edu

Noah Miller
nsmiller@usc.edu

Mehreen Mookerjee
mehreen.mookerjee@zu.ac.ae

[1] University of Southern California, Los Angeles, USA

[2] National Bureau of Economic Research (NBER), Cambridge, USA

[3] Zayed University, Dubai, UAE

[4] Carnegie Mellon University, Pittsburgh, USA

[5] Institute of Labor Economics (IZA), Bonn, Germany