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CLIMATE ADAPTATION INDUCED BY EXISTING INSTITUTIONS

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ABSTRACT

This study conceptualizes and demonstrates empirically that existing non-climate policies can induce climate adaptation. Adaptation involves adjusting to or coping with climatic change with the goal of reducing our vulnerability to its harmful effects. We examine the impact of temperature on ambient ozone concentration in the United States from 1980-2013. Ozone is formed under warm temperatures, but regulated by the Clean Air Act. These air quality standards may act as a buffer against extreme increases in ambient ozone concentration. Indeed, adaptation in counties out of attainment with the standards is 107 percent larger than under attainment, implying substantial regulation-induced adaptation.

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I. Introduction

Understanding whether and how we can adapt to a changing climate is essential for individuals and policymakers seeking to develop efficient climate policies. By definition, adaptation involves adjusting to or coping with climatic change with the goal of reducing our vulnerability to its harmful effects. Existing non-climate policies may facilitate climate adaptation, even if that is not their expressed or original purpose. This study conceptualizes and demonstrates that possibility in the context of the production of pollution – the impact of temperature on ambient "bad" ozone in the United States from 1980-2013. Ozone is formed by a Leontief-like production function of nitrogen oxides (NOx) and volatile organic compounds (VOCs) under sunlight and warm temperatures; hence, affected by climate change. Furthermore, ambient ozone is a pollution externality regulated by the Clean Air Act.

There is a broad class of existing non-climate policies that may help us cope with the consequences of climate change. They affect outcomes from major sectors of the economy whose production function is *indirectly* related to climate such as health, habitation, and safety.[1] Publicly-funded health care may assist individuals with heat-related illnesses, reducing mortality.[2] Those working outdoors such as agriculture and construction workers are particularly at risk. Housing policy that relocates households out of slums and informal settlements may also incidentally decrease fatalities and property losses from floods or landslides. This is especially important in developing countries, where slums are a distinctive feature of the urban landscape. Law enforcement and the military may also act as a buffer against climate-related crime and conflict.[3] These *co-benefits* of non-climate policy in terms

[1]This is on top of the *direct* effects of the provision of public goods and other government programs facilitating adaptation to climate change. Dell, Jones and Olken (2014) note that snowfalls that once in a while disrupts Southern U.S. states have negligible effects in the Northeast, in part because of policy-induced investments in snow removal. Similarly, around the world, governments have incentivized the development of crop varieties that are better suited for a changing climate (e.g., Olmstead and Rhode, 2008, 2011*a*,*b*).

[2]For evidence on the effects of extreme weather on mortality, see Deschenes and Moretti (2009); Deschenes and Greenstone (2011); Barreca et al. (2016); Heutel, Miller and Molitor (forthcoming). Mullins and White (2020) show that access to health care can indeed mitigate the effects of temperature on mortality.

[3]Ranson (2014), for example, estimates large impacts of climate change on crime in the United States, and Burke, Hsiang and Miguel (2015) review the broad literature on the links between climate and conflict.

of induced climate adaptation should be accounted for in the design and evaluation of public policy.

To understand the mechanism behind *regulation-induced adaptation* in our setting, consider a location where emissions of ozone precursors are under control in the baseline. If a rise in temperature leads to more intense ozone formation and the violation of the National Ambient Air Quality Standards (NAAQS), economic agents will be 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 temperatures, we refer to the resulting decline in ozone levels as adaptation to climate change induced by the ozone NAAQS regulations. At the end of the day, the pollution shocks triggered by climate change may be attenuated by adjustments induced by the existing Clean Air Act regulations.[4]

The insight that *existing* policies established for reasons unrelated to climate change may mimic key incentives of comprehensive climate policy goes to the heart of the second-best theory (Lipsey and Lancaster, 1956; Harberger, 1964, 1971, 1974; Hines, 1999; Goulder and Williams, 2003). When the outcome of interest arises from market failures, climate change may exacerbate those failures (e.g., Goulder and Parry, 2008; Bento et al., 2014), but existing non-climate policies will be there to smooth out the climate impacts.[5] Although economic theory provides clear guidance on addressing externalities, it has proven politically difficult to create new policies to combat climate change, the most significant of all environmental

[4]This is not a new use of the term climate adaptation. In the context of responses to natural disasters, 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).

[5]In contrast, and absent market failures, if government policy distorts private behavior, then individuals and firms might abstain from adaptive behavior. Annan and Schlenker (2015), for example, show that insured farmers may not engage in the optimal protection against extreme heat because crop losses are covered by the federal crop insurance program. Similarly, Deryugina (2017) provides evidence suggesting that *non-disaster* government transfers to disaster-prone areas – such as unemployment benefits – "may counteract the natural tendencies for out-migration from those areas" (Dell, Jones and Olken, 2014).

externalities (Aldy, Barrett and Stavins, 2003; Nordhaus, 2019; Aldy and Zeckhauser, 2020; Goulder, 2020). Thus, until first-best climate policy is enacted, it may be relatively easier for existing policy to be modestly adjusted to maximize adaptation co-benefits.[6]

Examining the degree of adaptation to climate change induced by existing air quality standards regarding ambient ozone is an ideal setting to study *regulation-induced adaptation*. Ambient "bad" ozone is not emitted directly into the air, but rather formed rapidly by Leontief-like chemical reactions between NOx and VOCs in the presence of sunlight and warm temperatures. Therefore, climate change will increase ozone concentration in the near future (e.g., Jacob and Winner, 2009). Moreover, ambient ozone is regulated by the Clean Air Act due to its effects on human health and the environment (e.g., Neidell, 2009; Moretti and Neidell, 2011; Graff Zivin and Neidell, 2012; McGrath et al., 2015; Deschenes, Greenstone and Shapiro, 2017), and such regulations may be effective in reducing ambient ozone concentrations (e.g., Henderson, 1996; Auffhammer and Kellogg, 2011; Deschenes, Greenstone and Shapiro, 2017). Because ambient ozone concentration is the result of pollution externalities generated by economic agents, these corrective policies not only address this market failure, but also indirectly induce climate adaptation.

We leverage a unifying approach to estimate climate impacts, and infer the empirical importance of adaptation induced by existing regulations. We build on Bento et al. (2020), and use variation in both weather and climate to uncover the effects of both short- and long-run variation in the *same* estimating equation. Inspired by Dell, Jones and Olken (2009, 2012, 2014), our measure of adaptation is derived *directly* from the difference between the responses to weather shocks and climatic changes; hence, unlike previous approaches, assessing its statistical significance is straightforward. In addition, because those are responses by the *same* economic agents, our unifying approach does not require extrapolation of weather responses over time and space to infer adaptation. Indeed, analogous to the Lucas Critique

[6] At the same time, economic agents may continue to rely on market forces to adjust to climate change. Hornbeck (2012) and Hornbeck and Naidu (2014), for example, highlight migration out of affected areas; and Barreca et al. (2016) call attention to the diffusion of existing technologies, such as air conditioning.

(Lucas, 1976), preferences may not be constant across time and space. In the end, our measure of regulation-induced adaptation is the difference between adaptation in counties in and out of attainment with the ozone NAAQS.[7] This strategy is only possible because once we recover a measure of adaptation from responses to weather shocks and longer-term climatic changes by the *same* economic agents, then we can compare the degree of adaptation across counties with different attainment status.

Our results demonstrate that existing policies unrelated to climate change can indeed facilitate adaptation, and the magnitude of the effect is of economic significance. The estimate of adaptation in nonattainment counties is about 107 percent larger than in attainment counties.[8] This finding is robust to a wide variety of sample restrictions and specification checks, such as accounting for alternative climate measurement, different periods of adjustment, distance to the NAAQS threshold for nonattaiment, constant or switching nonattainment status, and competing regulations for ozone precursors, among others.

This study makes three main contributions to the literature. First, it provides the first credible evidence that existing non-climate policy can be used as a buffer to climate shocks and still induce climate adaptation. Previous work has shown that although government programs may smooth out negative shocks associated with climate change, they might inadvertently inhibit adaptive behavior (e.g., Deryugina, 2017).[9] Second, it demonstrates that existing government policy may provide an alternative catalyst for adaptation to climate change beyond market forces and private responses. Prior literature has highlighted, for example, migration out of affected areas (e.g., Hornbeck, 2012; Hornbeck and Naidu, 2014; Deryugina and Molitor, 2020) and diffusion of existing technology (e.g., Barreca et al., 2016).

[7]Counties violating the air quality standards are required to take costly action to reduce emissions of ozone precursors to bring ozone levels below the standards, even when the violation may have been caused by rising average temperatures. Thus, there may be more climate adaptation in counties out of attainment.

[8]The magnitude of the regulation-induced adaptation associated with a 1°C increase in temperature is roughly 0.33 parts per billion (ppb). Because the impact of a 1°C temperature shock on ambient ozone concentration is approximately 2ppb in nonattainment counties, regulation-induced adaptation reduces that impact by about 17 percent.

[9]A notable exception is Mullins and White (2020), who find that the improved access to primary care services provided by the publicly-funded Community Health Centers (CHCs) rolled out across U.S. counties in the 1960s and 1970s moderates the heat-mortality relationship by 14.2 percent.

Third, it suggests that given the urgency to address climate change, existing policies can be used as a means to work towards that goal. Previous studies have examined the design and implementation of new regulations and policy, but have recognized their economic and political feasibility challenges (e.g., Aldy, Barrett and Stavins, 2003; Stavins, 2011; Nordhaus, 2019; Stavins, 2019; Aldy and Zeckhauser, 2020; Goulder, 2020).

The paper proceeds as follows. Section II presents a conceptual framework to understand how existing government regulations and policy may affect adaptation to climate change. Section III provides a background on the NAAQS for ambient ozone, ozone formation, and the data used in our analysis. Section IV introduces the empirical strategy; Section V reports and discusses the results; and Section VI concludes.

II. Conceptual Framework

A. Existing vs. New Regulations

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., Aldy, Barrett and Stavins, 2003; Stavins, 2011, 2019; Nordhaus, 2019; Aldy and Zeckhauser, 2020). Nevertheless, because of free-riding and political polarization, it has proven difficult to induce countries to join into an international agreement with significant emission reductions, or to enact federal legislation addressing climate change.

Recognizing the difficulty in implementing first-best climate policy, and the urgency in tackling the challenges of climate change, Goulder (2020) advocates for considerations 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 (Goulder, 2020).[10] In this study, we demonstrate that 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.

Our study focuses on the existing Clean Air Act (CAA) regulations – specifically the National Ambient Air Quality Standard (NAAQS). With the CAA Amendments of 1970, the EPA was authorized to set up and enforce a NAAQS for ambient ozone.[11] Since then, a nationwide network of 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.[12] 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.[13] In cases of persistent nonattainment the CAA mostly mandates command-and-control regulations, requiring that plants use the best available emission control technology (BACT) 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.

B. The Nature of Existing Regulations Inducing Adaptation

To understand how existing regulations such as the Clean Air Act's NAAQS may induce climate adaptation, let us consider a simple formalization using the sufficient statistic ap-

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

[12] 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; Graff Zivin and Neidell, 2012; Deschenes, Greenstone and Shapiro, 2017).

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

proach (Harberger, 1964; Chetty, 2009; Kleven, forthcoming). Assume that firms produce X units of a consumption good. They use $G(X)$ units of the numeraire Z, and generate P units of pollution, assumed for simplicity to be proportional to X. Since we are focusing on ozone pollution, and ozone formation depends on climate (C) as well, then we define $P \equiv F(X, C) = \delta(C)X$, with $\delta(.) > 0$ and $\delta_C(.) \equiv \delta'(.) > 0$.[14] Also, suppose that there is a continuum of consumers with wealth Y and quasilinear utility $U(X) + Z - r\delta(C)X$, where r is the marginal damage of ozone pollution.

Under profit and utility maximization, it can be shown (see Appendix C) that welfare (W) can be improved by reducing production.[15] This might be the case when the NAAQS for ambient ozone are binding. Because $dW \equiv dW(C) = -r\delta(C)dX > 0$ when $dX < 0$, these marginal reductions in X – e.g., to keep ozone concentrations below the NAAQS – would be welfare improving even in the case of a constant climate. In the case of climate change, however, the welfare gains from such reductions would be even greater, as the amount of pollution avoided by decreasing X would be proportionally larger. These further welfare gains, which are the monetized value of "regulation-induced adaptation" $\delta_C dX$, can be interpreted as a *co-benefit* of the NAAQS for ambient ozone:

$$\frac{dW}{dC} = -r\delta_C dX > 0. \tag{1}$$

Therefore, absent direct first-best climate policy, when climate is an input in the production of economic outcomes that arise from market failures such as ozone pollution, corrective policies targeting those outcomes may also lead to climate adaptation. In fact, in this second-best setting, policies correcting pre-existing market distortions may also address the externality of climate change (e.g., Goulder and Parry, 2008; Bento et al., 2014; Jacobsen et al., 2020). In the case of the NAAQS for ambient ozone, the standards not only deal with the externality of local air pollution, but also generate regulation-induced adaptation.[16]

[14]See Appendix A.2 for more details on ozone formation, and the role of climate.

[15]Indeed, the private optimum is not Pareto efficient because of the negative externality ozone pollution imposes on consumers. Hence, this is clearly a second-best setting (Lipsey and Lancaster, 1956).

[16]In contrast, when climate is an input in production but the output is a marketable good or service,

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 Figure 1. In Panel A, the y-axis represents the output – ozone formation – and the x-axis represents a composite index $I(.)$ of two inputs – NOx and VOCs – whose levels move along the production function $F(I(\text{NOx,VOCs}), \text{Climate})$ represented by the upward-sloping black line. $F(I(\text{NOx,VOCs}),$ Climate) is equivalent to the $F(\text{X,C})$ in the formalization above. The blue horizontal line represents the maximum ambient ozone concentration 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 it's precursors, VOCs and NOx, on the x- and y-axis respectively and resulting Ozone "isoquant" curves increasing up and to the right.

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 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 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 $I(\text{NOx,VOCs})$, 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.

policies considering output and/or input levels may not only distort economic agents' behavior and generate deadweight loss, but also potentially affect adaptive behavior. Annan and Schlenker (2015) illustrate the case of policies precluding adaptation: farmers may not engage in the optimal protection against harmful extreme heat because the resulting crop losses are covered by the federal crop insurance program. On the other hand, policies such as the federal air conditioning subsidies for low-income families would also generate deadweight loss, but could induce adaptation to climate change (Barreca et al., 2016). In this case, policymakers could weigh these costs and benefits in their decision process, in addition to equity considerations.

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. Thus, they are adapting to climate change because of the ozone NAAQS regulation, that is, they are engaging in regulation-induced adaptation.[17]

III. Data and Data Descriptions

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.

A. 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. We generate an indicator for 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

[17] 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, forthcoming). 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.

with NAAQS for ambient ozone (USEPA, 2004, p.23954).[18]

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, 2015*a*). 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), 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.[19] Our final sample consists of valid ozone measurements for a total of 5,139,129 monitor-days.[20]

[18] 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"* (USEPA, 2004, p.23954).

[19] 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.

[20] Appendix Figure A1 depicts the evolution of ambient ozone monitors over the three decades in our

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 1950-2013, because we need 30 years of data prior to the period of analysis to construct a moving average measure of climate.[21] 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.[22]

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

To give a sense of the data, Figure 2 illustrates the evolution of ozone concentrations and the proportion of counties in nonattainment over our sample period, while Figure 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 1980-2013 in the United States. The sample is split according to whether counties were in or out of attainment with the NAAQS for ambient ozone, established in 1979. Counties out of compliance with the NAAQS experienced, on average, a steeper

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 1,361 in the 1980s to over 1,851 in the 2000s. The number of monitored counties also grew from roughly 585 in the 1980s to over 840 in the 2000s. While Muller and Ruud (2018) find that compliance with the NAAQS for ambient ozone is not consistently associated with network composition, Grainger, Schreiber and Chang (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.

[21] 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.

[22] 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 30km. As will be discussed later, our results do not seem sensitive to these choices.

reduction in the daily maximum ozone levels than counties in compliance. We will argue that part of that reduction is associated with regulation-induced adaptation.[23]

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 our sample counties out of attainment increased more than 50 percent. Such a jump is not observed in the implementation of the 2008 revision, however. In this case, the share of counties in nonattainment remained stable around 0.3. 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.[24] 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.[25] Using our final sample,

[23] 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.

[24] 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. In our robustness checks we examine the sensitivity of our results to both shortening the number of years over which temperature is averaged, and by using a *daily* rather than monthly moving-average.

[25] Appendix Figure A6 presents a similar illustration to Figure 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 1980-2013.

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.

IV. 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 $\delta_C dX$ in Equation (1), the up-to-scale measure of regulation-induced adaptation. Thus, with an estimate of r – the marginal damage of ozone pollution – from the literature (e.g., Deschenes, Greenstone and Shapiro, 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 – the cross-sectional approach to estimate the impact of climate change on economic outcomes (e.g., Mendelsohn, Nordhaus and Shaw, 1994; Schlenker, Hanemann and Fisher, 2005), and the panel fixed-effects approach to estimate the impact of weather shocks (e.g., Deschenes and Greenstone, 2007; Schlenker and Roberts, 2009) – identifying both weather and climate impacts in the same equation. Inspired by Dell, Jones and Olken (2009, 2012, 2014), our *direct* measure of adaptation is the difference between short-run weather responses, which are approximately exclusive of adaptation, and long-run climate responses, which are potentially inclusive of adaptation. Since they are estimated in the same equation, our method allows for a straightforward test of the statistical significance of our measure of adaptation.

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. 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, Miller and Molitor, 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).

Our 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 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 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 the year prior to the measurement of the outcome variables.[26]

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

[26] A graphical representation of our decomposition has been 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.

shocks (Lovell, 1963, Theorem 4.1, p.1001).[27] 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.

Estimating climate impacts. As a first step, we decompose the observed daily maximum temperature into a norm and a shock. The norm is operationalized by the 30-year monthly moving average (MA).[28] The shock is merely the deviation of the observed temperature from that norm. Because ozone formation is directly tied to temperature, as discussed in Section III, the impact of temperature on ambient ozone is the focus of our analysis. Given that decomposition, we estimate the following equation:

$$\begin{aligned} Ozone_{it} = {} & \beta_N^W (Temp_{it}^W \times Nonattain_{c,y-3}) + \beta_N^C (Temp_{im}^C \times Nonattain_{c,y-3}) \\ & + \beta_A^W (Temp_{it}^W \times Attain_{c,y-3}) + \beta_A^C (Temp_{im}^C \times Attain_{c,y-3}) \\ & + X_{it}\gamma + \eta_{is} + \phi_{rsy} + \epsilon_{it}, \end{aligned} \tag{2}$$

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 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

[27] "*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).

[28] 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.

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. 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) point out that higher water vapor in the future climate may decrease ambient ozone concentration.[29] η represents monitor-by-season fixed effects, ϕ climate-region-by-season-by-year fixed effects, and ϵ an idiosyncratic term.[30]

We exploit plausibly random, daily variation in weather, and monthly variation in climate normals to identify the impact of 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; 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.

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

[29] 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.

[30] 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.

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 and technological progress.

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 interannual 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 Figure 2: from attainment to nonattainment, or vice versa.

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 Equation (2). 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, Jones and Olken, 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.[31] 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. 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, and other Clean Air Act regulations related to ozone – for example, restrictions on the chemical composition of gasoline, intended to reduce VOC emissions from mobile sources (Auffhammer and Kellogg, 2011), and the NOx Budget Trading Program (Deschenes, Greenstone and Shapiro, 2017).

Once we have measured adaptation in both attainment and nonattainment counties, we can express adaptation induced by the NAAQS for ambient ozone matching Equation (1) as

$$RIA \equiv \underbrace{(\beta^W - \beta^C)}_{\delta_C} \times \underbrace{(\mathbb{1}_N - \mathbb{1}_A)}_{dX} = (\beta_N^W - \beta_N^C) - (\beta_A^W - \beta_A^C). \tag{3}$$

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

[31] 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 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.

to obtain a coefficient and standard error for the measure of regulation-induced adaptation (RIA), and proceed with statistical inference.

V. Results

We begin by presenting our main 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 – which we termed regulation-induced adaptation. We then discuss the robustness of our results to the consideration of the distance of ozone concentrations from the NAAQS threshold, and accounting for competing input regulations on ozone precursors in the analysis. 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, among others. Finally, we examine heterogeneity in our recovered measure of adaptive response by local (county-level) factors such as belief in climate change or precursor-limited ambient atmosphere as well as over time and across the temperature distribution.

A. 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 Equation (2), 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 1.65ppb. This can be seen as a benchmark for the ozone response to temperature because of the limited opportunities to adapt in the short run.[32] 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 1.16ppb, 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 – 0.49ppb – 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 treatment effects by attainment status, as specified in Equation (2). 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 their ozone responses to temperature changes are significantly lower. Column (4) shows that adaptation in nonattainment counties is over 107 percent larger than in attainment counties. As defined in Equation (3), the difference between those two adaptation estimates – 0.33ppb – is our measure of regulation-induced adaptation, shown at the bottom of column (4). 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 impact on ambient ozone concentrations (Henderson, 1996).

Although it is not the main focus of our study, it is imperative to discuss the degree of adaptation in attainment counties. The second estimate in column (4) – 0.31 ppb – indicates that adaptive behavior is also present in those jurisdictions. The underlying reasons might be technological innovation and market forces, as highlighted in previous studies (e.g., Olmstead and Rhode, 2011*a*,*b*; Hornbeck, 2012; Hornbeck and Naidu, 2014; Barreca et al., 2016),

[32] We see it as a benchmark because we assume that economic agents are not be 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.

other regulations affecting both attainment and nonattainment counties (e.g., Auffhammer and Kellogg, 2011; Deschenes, Greenstone and Shapiro, 2017), or even preventive responses in counties with ozone readings near the threshold of the NAAQS for ambient ozone, as explained below. In that sense, our measure of regulation-induced adaptation might represent a lower bound of how ozone NAAQS encourage adaptive behavior.

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

B. Robustness Checks

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 in every game is the unique dominant-strategy Nash equilibrium, following familiar backward-induction arguments. But if played an infinite (or an unknown) number of times, now the preferred strategy is not to play a Nash strategy of the stage game, but to cooperate and play a socially optimum strategy.

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.[33]

Table 2 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 20-40 percent away from the threshold in Panel B, and over 40 percent away from the threshold in Panel C. The observations within 20 percent of the NAAQS threshold comprise about 13 percent of the overall sample. As

[33]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 138ppb, hence above the threshold of 120ppb) 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.

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.

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, Greenstone and Shapiro, 2017), and (iii) the Regional Clean Air Incentives Market (RECLAIM) NOx and SOx emissions trading program (Fowlie, Holland and Mansur, 2012). Because our focus in this study is to estimate climate adaptation induced 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.

Auffhammer and Kellogg (2011) demonstrate that the 1980s and 1990s 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. This is not surprising because the regulation was extended to all counties in California – attainment and nonattainment counties.

Deschenes, Greenstone and Shapiro (2017) and Fowlie, Holland and Mansur (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, Greenstone and Shapiro (2017) operated a cap-and-trade system for over 2,500 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.[34] The RECLAIM NOx and SOx trading program examined by Fowlie, Holland and Mansur (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.[35] Table 3 reports the results excluding NBP states in columns (3) and (4), and excluding RECLAIM counties in columns (5) and (6). The

[34]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, Greenstone and Shapiro, 2017).

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

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 not surprising because they affected both attainment and nonattainment counties.

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 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 B2. 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 B3 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; while Table B4 examines additional sample restrictions – splitting the sample into counties that maintained the same NAAQS designation across the entire sample period, and those that switched their NAAQS designation at least once.

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 analyses are relatively stable across the alternative approaches. Additionally, although it has been shown that, e.g., manufacturing plants have relocated in response to ozone nonattainment designations (Henderson, 1996; Becker and Henderson, 2000), results in Table B6 suggest that firms are not responding differentially based on climatic variables. Lastly, observe 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 B7. 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 analysis.

C. 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: local belief in climate change, local atmospheric composition, across time, and across the temperature distribution.

Adaptation by local climate beliefs and local atmospheric composition. So far we have demonstrated that existing government regulations and policy can be effective in inducing climate adaptation. Now, we examine whether local climate change beliefs, or the underlying composition of the local atmosphere may alter the effectiveness of such policies. 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.

Table B8 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). 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.[36] 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.[37]

Similarly, Table B11 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. 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.

Adaptation across time and temperature. While the above analyses examine heterogeneity in adaptive response across inherently spatial dimensions, areas with different beliefs or different underlying atmospheric conditions, one may wonder how adaptation varies across other dimensions, such as time or the temperature distribution itself. When we examine the estimates by decade, as reported in Appendix Table B12, the magnitude of regulation-

[36] 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 B9 provides summary statistics of basic demographic characteristics across these three county groupings using data from the 2006-2010 5-year American Community Survey.

[37] 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 B10.

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. Examining the estimates across the temperature distribution, in Tables B13a and B13b, we see an almost doubling of regulation-induced adaptation above 30°C, and almost tripling above 35°C, relative to days where temperature was below 30°C – in line with the idea that nonattainment counties may be especially focusing adaptive efforts on those hottest months where they would be most likely to exceed the NAAQS threshold.

D. 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 Section II, 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, Greenstone and Shapiro (2017). As detailed in Equation (3), all of these elements can be mapped directly into the components of Equation (1), 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 the components of Equation (1) to each of these three "sufficient statistics," summing across every county n in the set of counties ever designated as nonattainment (NA) within our sample period:

$$\Delta W \approx -\sum_{n \in NA} \underbrace{r}_{DGS} \underbrace{\delta_C \Delta X_n}_{Table1} \underbrace{\Delta C_n}_{Vose}, \tag{4}$$

where r is treated as a fixed value, approximately equal to \$1.75 million (2015 US) per county per year, following Deschenes, Greenstone and Shapiro (2017). The value of ΔC

varies depending on the chosen climate projection from Vose et al. (2017), while $\delta_C \Delta X$ 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.[38]

Table 4 presents the costs of climate change, the savings from overall adaptation, and particularly the savings from regulation-induced adaptation – the co-benefit of the CAA which is the focus of this study. 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 – $\beta_N^W - \beta_N^C$ – and the row labeled "regulation-induced adaptation" displays the portion of the adaptation due to the NAAQS for ambient ozone – RIA as in Equation (3).

Table 4, column (1), reports the costs associated with increased ambient ozone, and potential savings from adaptation, from a 1°C increase in temperature – $\Delta C = 1$. 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 Equation (1). In the next four columns, all estimates are scaled up with the temperature projections from Vose

[38] As defined in Equation (1), emissions are taken as proportional to X; thus, although Equation (4) focuses on changes in ozone concentration, for simplicity and consistency we represent it here as ΔX.

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. These are nontrivial additional welfare gains brought about by the air quality standards regarding ambient ozone.

VI. Concluding Remarks

This study conceptualized and presented the first credible estimates of regulation-induced adaptation. In the absence of new international agreements or new federal legislation to tackle climate change directly, we have demonstrated conceptually and empirically that *existing* government regulations and policy established for reasons unrelated to climate change may be already inducing adaptation to climate change. We examined the impact of temperature changes on ambient ozone concentration in the United States from 1980-2013, and measured the role of regulation-induced adaptation. Our main finding was that adaptation in counties out of attainment with air quality standards was 107 percent larger than in counties under attainment, implying substantial regulation-induced adaptation.

By establishing that government regulations and policy unrelated to climate change are enhancing climate adaptation, our study points to an alternative set of incentives encouraging adaptive behavior besides innovation and market forces, which have been highlighted in previous research.[39] At the same time, our findings reveal a different role for public policy relative to a few other studies which caution that government actions intended to protect the public may reduce the incentive to engage in private self-protection.[40] Our results differ from these studies because, in our case, the regulation we examined corrects a market failure – an air pollution externality – whereas the government programs examined in prior work may

[39] Olmstead and Rhode (2008, 2011*a*,*b*) highlighted crop choice and biological innovation in agriculture; Hornbeck (2012), Hornbeck and Naidu (2014), and Deryugina and Molitor (2020) pointed to migration; and Barreca et al. (2016) called attention to changes in the use of existing technologies, such as air conditioning.

[40] Annan and Schlenker (2015) found that the federal crop insurance program deterred farmers from engaging in optimal protection against extreme heat. Similarly, Deryugina (2017) showed that social safety nets not specifically targeting areas affected by extreme weather events may have discouraged out-migration.

have distorted private behavior. Again, the insight here goes to the heart of the second-best theory. When the outcome of interest is the result of market failures, climate change can exacerbate the magnitude of the local unpriced externality. Nevertheless, existing regulations created for reasons unrelated to climate change can mimic incentives of nonexistent or incomplete climate policy, and induce climate adaptation.[41] It is imperative to reiterate, however, that our findings do not imply that efforts to enact comprehensive climate policy should be undermined. Rather, existing regulations such as this should be recognized as potentially valuable stepping stones towards reducing the cost of inaction (Stavins, 2019; Goulder, 2020).

To the best of our knowledge, we are among the first to provide direct estimates of *incidental* benefits of current public policy in terms of climate adaptation. Because we are studying climate change, the first-best policy fostering adaptation should be carbon pricing. When that option is politically infeasible, however, a second-best solution can be implementing or strengthening policies correcting market failures associated with outcomes that depend on climate. The NAAQS for ambient ozone – the focus of our study – not only address an externality but also stimulate adaptation because climate is an input in ozone formation.

Our findings may contribute to the design of pollution control policy as well. The EPA has recently reviewed the NAAQS for ambient ozone, and decided to maintain the current threshold of 70ppb (USEPA, 2020), but will revisit the standard again in 2025. According to the 2015 EPA's Final Ozone NAAQS Regulatory Impact Analysis (USEPA, 2015*b*), the annual nationwide costs to reduce the ambient ozone standards by 1ppb were approximately $296 million (2015 USD).[42] Now, under the RCP 4.5 climate change scenario for mid-century

[41] Another example of regulation-induced adaptation may arise in the context of the Clean Water Act (Keiser and Shapiro, 2019*a*,*b*). The cleaning of the rivers might allow drought-prone locations to have alternative sources of drinking water. Think of the western region of the United States, where droughts may become more frequent with climate change. Water shortages may be addressed by the rivers cleaned up by the establishment of the Clean Water Act.

[42] For reference, the 1997 NAAQS for ambient ozone (implemented in 2004 due to lawsuits) was 80ppb. That was revised downward to 75ppb in 2008, and 70ppb in 2015. Also, ozone-only benefits reflect short-term exposure impacts, and as such are assumed to occur in the same year as ambient ozone reductions.

United States, regulation-induced adaptation from the projected 1.4°C increase in average temperature would reduce the climate impact on ozone concentration by 0.46ppb. This represents an additional $412 million in indirect adaptation-related benefits for the 509 counties that had been ever out of attainment with the ozone NAAQS in the period of our analysis, accounting for about two thirds of the U.S. population. Thus, further reductions to the NAAQS threshold, while incurring additional costs, would also likely incur additional co-benefits as more counties, now facing nonattainment designation under the lowered standard, engage in regulation-induced adaptation. Based on our back of the envelope calculations, the regulation-induced adaptation co-benefit alone may be enough to offset the cost of marginal reductions in the NAAQS. Therefore, it is urgent that EPA takes climate change into account in regulatory impact analyses of ambient ozone standards.

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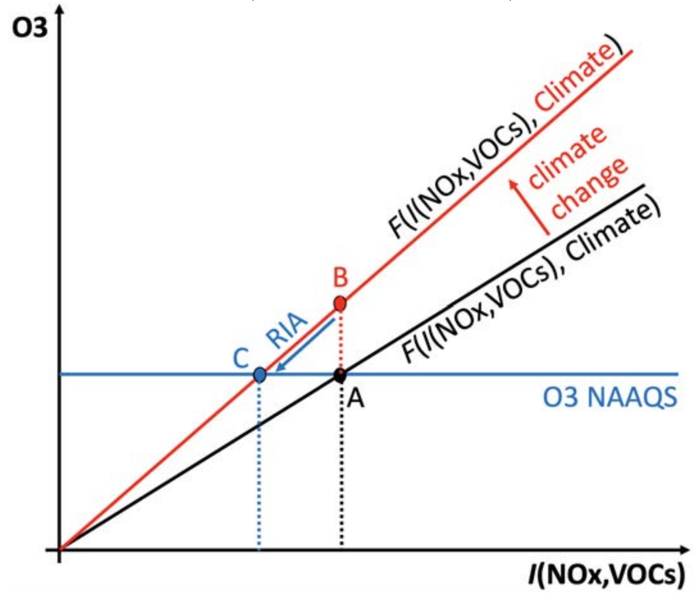
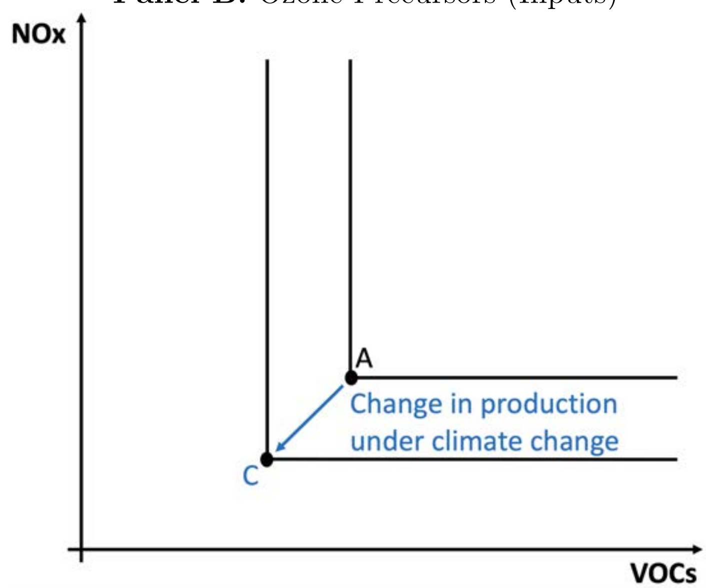
Figure 1: Conceptual Framework on Regulation-Induced Adaptation

Panel A. Ozone, Ozone Precursors, and Climate

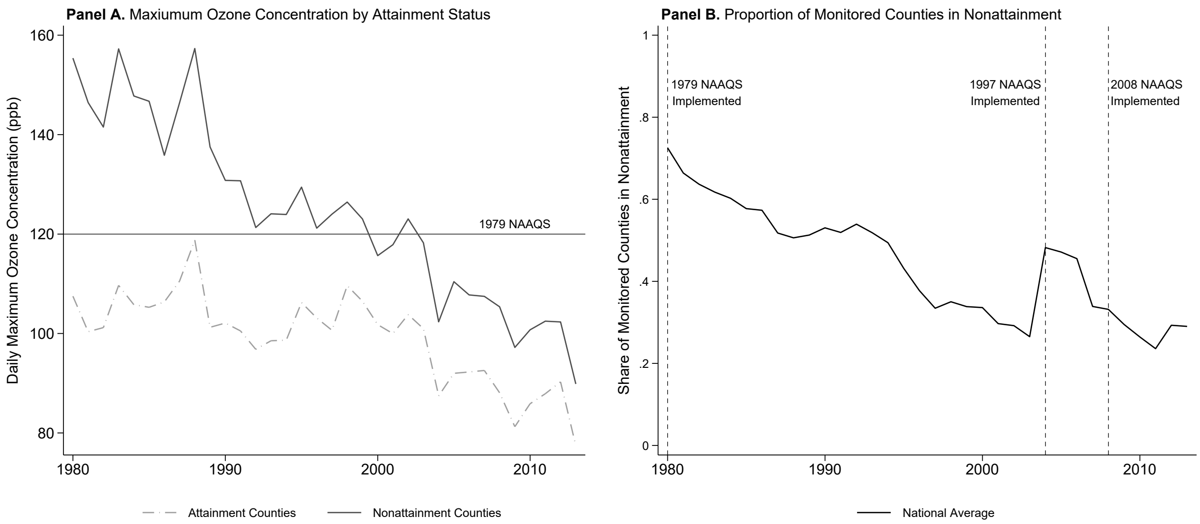


Panel B. Ozone Precursors (Inputs)



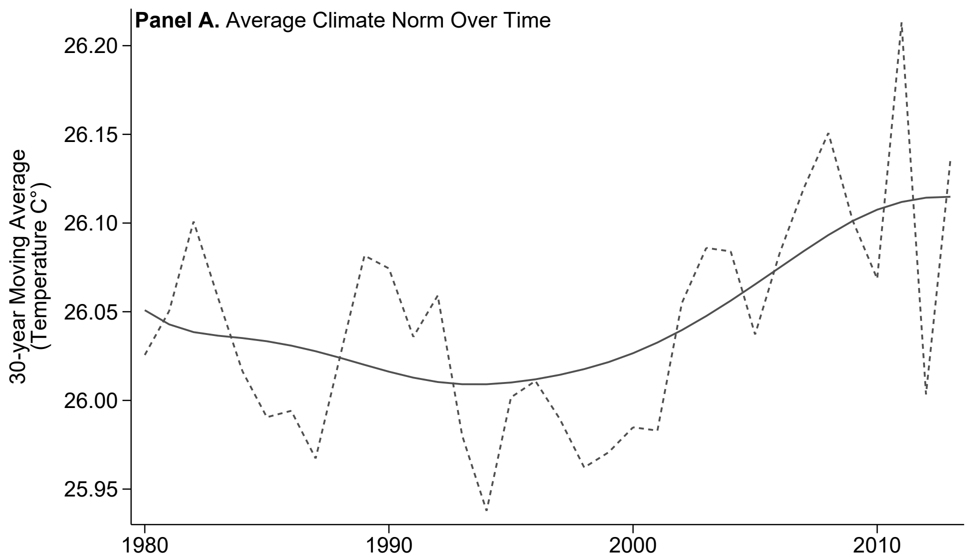
Notes: This figure provides a schematic representation of the conceptual framework used in our analysis. In the top panel, the y-axis represents the output – ozone formation – and the x-axis represents a composite index $I(.)$ of two inputs – NOx and VOCs – whose levels move along the linear production function $F(I(\text{NOx,VOCs}), \text{Climate})$ 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 $I(\text{NOx,VOCs})$, ozone concentration increases to point B. Because the county is now out of compliance with the 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. In fact, 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.

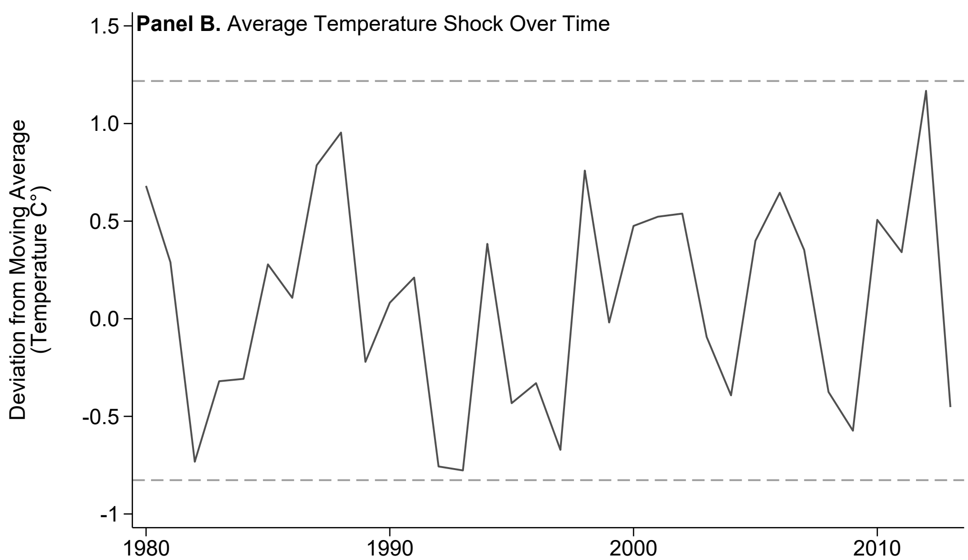
Figure 2: Evolution of Maximum Ozone Concentration and Counties in Nonattainment



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 average ozone levels at the margin of nonattainment.

Figure 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.

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 x Shock		1.990***		
		(0.079)		
Nonattainment x Norm		1.351***		0.639***
		(0.067)		(0.054)
Attainment x Shock		1.263***		
		(0.027)		
Attainment x 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 Equation (2). 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 Equation (**??**), 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.

Table 2: Results by Distance of Ozone Concentrations to NAAQS Threshold

	Panel A. Ozone (ppb) Within 20% of NAAQS Threshold				
	Non-Attainment		Attainment		Induced
	Ozone (ppb)	Adaptation	Ozone (ppb)	Adaptation	Adaptation
	(1)	(2)	(3)	(4)	(5)
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)
	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)
	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)
All Controls			Yes		
Observations			5,139,209		
R^2			0.709		

Notes: This table reports results from our main specification in Equation (2) 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 120ppb 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 80ppb or higher, and the 2008 update further reduced this to 75ppb. Standard errors are clustered at the county level. ***, **, and * represent significance at 1%, 5% and 10%, respectively.

Table 3: Accounting for Competing Input Regulations Aiming at Ambient Ozone Reductions

	VOC Regulations (Excluding California)		NOx Regulations (Excluding NBP States)		NOx Regulations (Excluding RECLAIM Counties)	
	Ozone (ppb)	Adaptation	Ozone (ppb)	Adaptation	Ozone (ppb)	Adaptation
	(1)	(2)	(3)	(4)	(5)	(6)
Nonattainment x Shock	2.032***		2.050***		1.987***	
	(0.092)		(0.090)		(0.082)	
Nonattainment x Norm	1.370***	0.662***	1.430***	0.620***	1.320***	0.667***
	(0.061)	(0.064)	(0.080)	(0.062)	(0.055)	(0.061)
Attainment x Shock	1.275***		1.267***		1.263***	
	(0.028)		(0.031)		(0.027)	
Attainment x Norm	0.970***	0.305***	0.978***	0.290***	0.946***	0.317***
	(0.034)	(0.028)	(0.041)	(0.034)	(0.033)	(0.029)
Regulation Induced		0.358***		0.331***		0.349***
		(0.065)		(0.063)		(0.062)
All Controls	Yes		Yes		Yes	
Observations	4,631,413		4,338,183		5,008,323	
R^2	0.432		0.443		0.439	

Notes: This table reports results from our main specification in Equation (2) 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, Greenstone and Shapiro, 2017), and (iii) the Regional Clean Air Incentives Market (RECLAIM) NOx and SOx emissions trading program (Fowlie, Holland and Mansur, 2012). 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. The implied adaptation estimates presented in columns (2), (4), and (6), are derived from the estimates reported in columns (1), (3), and (5), 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: 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	1,766	2,473	4,946	2,826	8,479
With Adaptation	1,199	1,679	3,357	1,918	5,755
Savings (Millions 2015 USD/year)					
From Adaptation	567	794	1,589	908	2,723
Regulation Induced Adaptation	294	412	824	471	1,412

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, Greenstone and Shapiro, 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 (RCP8.5). 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 RCP8.5 (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.