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Air Pollution Causes Violent Crime[*]

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Abstract

Scientific evidence is that ozone exposure induces aggression, irritability, impulsivity and loss-of-control in humans, mice, monkeys and other animals. Consistent with this we use data from Los Angeles to generate the first evidence causally linking day-to-day variations in air quality to violent crime. The effect is substantial. Using IV methods with wind direction as instrument our preferred specification points to a 17% increase in assaults for a 10 ppb increase in daily fine particulate pollution. We also identify very small positive impacts of carbon monoxide (CO). The results satisfy a wide set of robustness checks. Cost-benefit analyses that fail to account for these effects will substantially under-estimate the case for air quality regulation.

Key words: *Valuation of air quality, Non-health impacts of pollution, crime.*

Résumé

Plusieurs études scientifiques démontrent que l'exposition à l'ozone induit plus d'agressions, d'irritabilité, d'impulsivité et de pertes de contrôle chez les humains, les souris, les singes et plusieurs autres animaux. Dans le même ordre d'idée, nous utilisons des données de la ville de Los Angeles afin de démontrer pour la première fois qu'il y a une relation causale entre les variations journalières dans la qualité de l'air et le nombre de crimes violents. L'effet documenté est substantiel. Nous utilisons des méthodes VI avec la direction du vent comme instrument et estimons que de passer du quartile le plus propre au quartile le plus sale au cours d'une journée cause une augmentation de 13-48% dans le nombre d'agressions. Les résultats sont robustes à un grand nombre de tests. Des analyses coûts-bénéfices qui ne prennent pas en compte ces effets vont sous-estimer considérablement l'argumentaire justifiant l'existence d'une réglementation de la qualité de l'air.

Mots clés : *Évaluation de la qualité de l'air, effets de la pollution non liés à la santé.*

1 Introduction

Economic analysis of policies aimed at improving air quality has focused on health. There is a long-established body of research linking air pollution to adverse health outcomes,[1] and health benefits dominate the "benefits" column of cost-benefit evaluations of air quality regulations.

However, recent research points to the impact of air pollution on a broader set of economic and socioeconomic outcomes. For example, Chang et al. (2014) and Zivin and Neidell (2012) find compelling evidence of the impact of short-term variations in air pollution on worker productivity in physical task settings (fruit picking and handling). Lavy et al. (2014) and Bharadwaj et al. (2014) find negative effects on cognitive performance in the context of student performance in standardized exams.

Pollution serves to alter - quite literally - the air that we breathe. It can change the way we feel and the way we react. As such, it is not far-fetched to conjecture that variations in air quality, by affecting our emotional state or in other ways, might influence a wider set of human outcomes. This study investigates the impact on violent crime. We provide below an overview of the biological evidence linking short-term exposure to air pollution (in particular ozone) to aggressivity, impulsivity, irritability and loss of self-control in humans and animals. However, a motivating example to hold in mind - and perhaps a crude metaphor for people in a polluted city - is that a pair of laboratory mice exposed to elevated levels of ozone for one hour are observed to fight sooner and more frequently than a control pair (Musi et al. (1993), Petruzzi et al. (1995)). We do not tie the analysis to a particular theoretical model of crime but have in mind some version of the sort of loss-of-control model used by Card and Dahl (2011).[2]

We provide the first evidence of a causal link from daily variations in ozone to same-day occurrences of violent crime. In particular combining environmental data with crime records from the city of Los Angeles between 2005 and 2013, we investigate the impact of short-term changes in ozone levels on aggregate daily number of criminal assaults. Ground level ozone is not emitted directly into the air but is created by chemical reactions between oxides of nitrogen (NO_x) and volatile organic compounds (VOCs) which occur rapidly in the presence of sunlight. Emissions from car exhausts, power stations, other industrial sites and chemical solvents are some of the major sources of NO_x and VOC. Ozone is the major constituent of photochemical smog and commonly used as a composite or summary measure of air quality.

Identifying a causal relationship between ozone exposure and violent crime poses a

[1]For instance look at Neidell (2009), Currie and Neidell (2005), Chay and Greenstone (2005), Graff Zivin and Neidell (2009), Moretti and Neidell (2011) and Currie et al. (2014).

[2]Specifically, Card and Dahl (2011) find that emotional shock (unexpected loss by a city's NFL team), leads to a roughly 10% increase in at-home violence. In our setting that individual-level threshold may itself be sensitive to environmental conditions, making people more prone to respond to emotional affront with violence.

number of challenges. First, there are two potentially important sources of measurement error. The underlying mechanisms point to the importance of pollution *exposure* which we are unable to observe directly. Rather we use as a proxy ambient pollution levels in the law enforcement agency level in which the crime is committed. Relatedly, exposure may be endogenous since individuals may engage in avoidance behavior (Neidell (2009) and Chay and Greenstone (2005)).[3] Second, weather variables such as temperature are known to effect crime directly (Ranson (2014)) but also influence ozone production. This provides a potential source of omitted variable bias insofar as we are unable to control fully for the effect of weather confounders.[4]

To address these concerns we use instrumental variables methods (IV) with wind direction as an instrument for ozone. A number of considerations point to wind direction being a good choice of instrument.

First, day to day variations in wind direction are well-understood to be an important determinant of air quality in Los Angeles. Many of the major sources of air pollution (including Los Angeles International Airport (LAX) and the Port of Los Angeles) sit on the coast to the west and southwest of the city. Westerly winds carry pollution inland and the abundant sunshine turns transferred pollution to ozone. Local topography - with high mountains close to the east and north-east - mean that the ozone-rich air is then 'pinned' over the city by the breeze, with little opportunity to escape. This process is well-understood by students of air quality in the city: "The high density of transportation, with cars, air traffic and shipping produces volatile organic compounds and oxides of nitrogen – the chemicals that turn into ozone. Sea breezes push them over the basin and the abundant sunlight transforms them into ozone, which is then trapped by the mountains to the east" (McCarty (2014)). Or as Suzanne Paulsen, Director of the UCLA Center for Clean Air sums it up: "The Los Angeles basin is unfortunately uniquely suited to ozone pollution. It's a combination of the ring of mountains, wind direction and lots of sources upwind that produces the high ozone" (quoted in McCarty (2014)). Statistically wind direction proves to be a strong instrument, delivering an F-statistic in excess of 170 in our preferred specification (against a usual rule-of-thumb benchmark of 10).

Second, although wind directions have a seasonal pattern there remains substantial day to day variation - driven by large-scale weather systems and a host of hard-to-predict local effects - which from the point of view of our study can be treated as random.[5]

[3]This is less of a problem for us than much of the health literature. We are not seeking a crime production function with ozone exposure as an input - analogous to the health production function commonly sought in the health economics literature. Rather we estimate a reduced form relationship between air quality and crime which could embody, for example, changes people make in their pattern of behavior on polluted days.

[4]A plethora of other things might plausibly impact short-run variations in violent crime. For example Dahl and Della Vigna (2009) evidence the role of violent movies playing in local theatres on assault rates.

[5]As indicated by Ahr (1932) winds start to move in straight lines only when the pressure gradient and the Coriolis force come into balance with each other. Near the earth's surface an additional element come into weight, which is friction. Winds passing near the earth's surface are most likely to experience

Third, it is difficult to think of a plausible direct link from wind direction to crime. In support of this we point to a large empirical literature on the meteorological determinants of crime makes no mention of the possibility of wind direction having any influence.[6] Validity of the instrument would also be compromised if wind direction were correlated with other unobservable short-run determinants of crime. To address this concern we use flexible controls for the air pressure and temperature - the two main meteorological factors impacting wind direction - in our regressions.

The results indicate a positive causal impact of variations in ozone pollution on number of assaults. OLS estimates indicate that there is a statistically significant 3.1% increase in daily number of assaults for a 10 ppb increase in the level of ozone. Our preferred IV estimates imply larger effects with a 10 ppb increase in ozone exposure causing a 19.4% increase in assaults. As expected the IV estimates are significantly larger reflecting attenuation bias to OLS estimation in the presence of measurement error.

Estimates prove robust in sign and significance across a range of specifications. In addition to OLS and IV estimation based on a wide variety of controls included in differing combinations we also report non-linear and lagged specifications. We also report the results of further robustness and falsification tests. (1) To address concerns that variations in violent crime may reflect changes in criminality more generally, for example, or variations in the crime detection/reporting propensities of police, as a falsification test we re-estimate our model using data on the largest class of non-violent crime (larceny) and find no significant effect of air pollution exposure. This is consistent with our hypothesis - and existing research - that air pollution predisposes people to increased violence. (2) To counter concerns that there may be something particular about Los Angeles we replicate the results for both violent and non-violent crime for a different city, namely Houston. Results for variations in both violent and non-violent crimes prove fully-robust in sign and significance to Los Angeles and similar in magnitude. (3) To address concerns generic in the design-based inference literature that something in the research design may *itself* be generating apparent causal effects we report the results of two different placebo tests (one pre-treatment, one post-treatment) for each of the OLS and IV regressions (following Lavy et al. (2014), Hartman and Hidalgo (2011) and others).

The layout of the rest of the paper is as follows. In Section 2, we provide a review of some pertinent literature. In Section 3, data sources are outlined. Sections 4 and 5 summarize our methodological challenges and our empirical strategy. Sections 6 presents our results. Section 7 reports further robustness and falsification checks. Section 8 concludes.

earth heat which lead to irregular wind tracks.

[6]For a few examples amongst many see Rotton and Frey (1985), Cohn (1990), Cohn and Rotton (2000), Rotton and Cohn (2000), Horrocks and Menclova (2011), and Ranson (2014).

2 Literature

This is the first paper that evidences a causal link from short-run (day-to-day) variations in pollution exposure to criminal outcomes. However, there are a number of strands of literature that provide potentially pertinent background and motivation.

First, research that links *long-term* childhood lead exposure to various negative behavioral outcomes - including criminality - in adolescence and adulthood. This is not about short-run variation, however it points to a positive correlation between the accumulation over years of persistent heavy metals in the body and brain and criminal behavior. This is outlined in Section 2.1.

Second, there is plentiful biological evidence linking ozone exposure not to crime itself, but to mood and emotional states that might sensibly be regarded as precursors or risk factors for violent criminal behavior. In terms of a Card and Dahl (2011) type loss of control model, for example, ozone inhalation might reduce (in some people) the threshold of annoyance that must be passed in order to trigger violence. Laboratory research shows that short-term exposure to ozone can have sizeable impacts on stress, irritability, impulsivity, aggressivity and loss-of-control in humans and a variety of animals. Various channels have been identified, including hormonal (through testosterone) and neuro-chemical (especially through serotonin). This literature is reviewed in Section 2.2 and provides a *theoretical* foundation for the *statistical* results in this paper.

The third small cluster of studies, outlined in Section 2.3, uses administrative data to link air pollution variations to non-crime outcomes that might be thought to be potential correlates with criminal behavior, such as psychiatric emergency calls and frequencies of violent suicide.

2.1 Lead

Long-term exposure to lead is an established contributor to delinquency and crime. Indeed, Needleman et al. (1996) assert that 20% of all crime in the United States could be lead-associated. Lead (and other heavy metals) accumulate in the brain and these accumulations are linked to a number of undesirable outcomes such as impaired auditory processing, reduced school performance, Attention-Deficit/Hyperactivity Disorder (ADHD) and inability to inhibit inappropriate responses (Rice (1996)).

Various empirical approaches are used to investigate the relationship between lead and crime. Using annual state level crime data for Columbia from 1985 to 2002, Reyes (2007) estimates the elasticity of violent crime with respect to childhood lead exposure to be about 0.8. Stretesky and Lynch (2004) exploit spatial variation in lead exposure across 2772 US counties to establish a similar link, with the greatest effect in the poorest areas. Nevin (2007) finds a strong, robust correlation between violent crime and preschool lead exposure in a panel of high-income countries.

Other studies use direct physiological data. For example, Needleman et al. (1996) show that bone lead levels can be used to predict delinquency and behavioral problems amongst teens. Pihl and Ervin (1990) compare hair samples from prisoners convicted of violent and non-violent crimes and find that cumulative exposure to toxic substances (including lead) to be higher in the violent group.

2.2 Experimental evidence: Humans and other animals

In laboratory experiments Musi et al. (1993) find that pairs of adult mice exposed to an elevated level of ozone for 1-hour have a higher tendency to fight than control pairs. This result is corroborated by, for example, Petruzzi et al. (1995). The time to first fight (latency) is shorter and subsequent attack episodes more frequent. Furthermore the subordinate mouse is more prone to engage in aggressive-defensive responses - 'fronting up' to the aggressor rather than retreating.

Chen et al. (2003) report that exposure of infant rhesus monkeys to ozone increases excitability, while Soulage et al. (2004) show that 5-hour ozone exposure impacts stress levels and aggressive behavior in rats. Allen et al. (2013) link ozone exposure to heightened impulsivity in mice.[7]

While none of these studies explore the mechanisms that might link pollution to mood or behavior, there are other strands of research that do.

Serotonin (5-Hydroxytrlptamine or 5-HT) is a primary neurotransmitter - one of the chemicals responsible for the flow of information in the brain and nervous system. Serotonin is an inhibitor and its key functions is to control impulsive and aggressive behavior (Coccaro et al. (2011)). The lower level of serotonin in the bloodstream is associated with less ability of an animal to control impulsive and aggressive behaviors.

Krueger et al. (1963) was the first study to identify short-term variations in air quality as an important cause of fluctuations in serotonin in the bloodstream. In more recent work Paz and Huitrón-Reséndiz (1996), González-Guevara et al. (2014) and Murphy et al. (2013) provide experimental evidence linking short-term ozone exposure to decreased level of serotonin in the brains of animals.[8]

Serotonin is well-known to affect several behaviors of potential interest to us. For

[7]It may not be obvious to all readers how the impulsivity of a mouse is measured. In fact animal behavioralists use methods similar in spirit to those that economists use to elicit discount rates from human subjects. In particular they use a waiting-for-reward setup in which the more patient a mouse is the greater the dose of sucrose pellets that it receives.

[8]Other neurotransmitters have also been implicated, but the mechanisms are not as well-understood. For example Kinawy (2009) find that rats exposed to the fumes of unleaded or leaded gasoline behave more aggressively than a control group exposed to clean air. Subsequent inspection of the brains showed variation in the levels not just of serotonin but other monoamine neurotransmitters such as dopamine and norepinephrine.

example, decreased serotonin is associated with an increased tendency to fight amongst rhesus monkeys (Faustman et al. (1993)) and with increased impulsive aggression in children (Frankle et al. (2005)). In a recent study that involved manipulating the serotonin levels of human subjects within a social experimental settings, Crockett et al. (2013) found that "serotonin-depleted participants were more likely to punish those who treated them unfairly, and were slower to accept fair exchanges". In their summary of the human literature (Siegel and Crockett, 2013, p. 42) note that "... a meta-analysis encompassing 175 independent samples and over 6,500 total participants reveals a reliable inverse relationship between serotonin and aggression". Given that criminal assault requires both an attacker and a victim, it may also important to mention that serotonin levels are positively correlated with harm-avoidance behavior in humans (Hansenne et al. (1999)) - in other words a serotonin-depleted individual is less likely to seek to avoid or flee from an aggressor.

While the neuro-chemical channel is a good candidate for linking ozone levels to crime, there are other biological possibilities. For example, Maney and Goodson (2011) survey the literature on the role played by *hormonal* mechanisms in animal aggression. Uboh et al. (2007), for example, provides experimental evidence causally-linking ozone exposure to substantially-elevated levels of testosterone in male rats. Testosterone is particularly linked to violent crime in humans (Dabbs Jr et al. (1995), Birger et al. (2003)).[9]

2.3 Some suggestive analyses of administrative data

There is a strand of literature that exploits administrative datasets to derive results that might be (at least contextually) helpful to us here.

Rotton and Frey (1985) provide a positive correlation between family disturbances and ozone concentrations in Dayton, Ohio for the period 1975 and 1976. As an early paper, their analysis is hampered by data availability issues (missing controls) and methodological constraints.

Two studies find a positive correlation between short-term air pollution and psychiatric admissions rates (Briere et al. (1983), Strahilevitz (1977)). If mental instability is

[9]Physiological research also indicates that exposure to common air pollutants leads to oxidative stress and neuro-inflammation - inflammation of nerve tissues in the body and the brain; "(c)onsistent with findings from human populations, animal studies in dogs, mice and rats show that air pollution components cause neuro-inflammation" (Levesque et al., 2011, p. 4). In a study on rats, Van Berlo et al. (2010) show that a 2-hour long exposure leads to an immediate spike in pro-inflammatory factors in the brain. Neuro-inflammation induced by pollution is linked to behavior in animals that if transferred to humans, might be pertinent to understanding some types of crime. Rammal et al. (2008) show a link between oxidative stress and behavior in male mice in a resident/intruder test. This is a standard class of experiment, in which an "intruder" mouse is introduced into the home cage of an incumbent. This test is used by animal behavioralists to study conflict and to measure the intensity with which an animal reacts to invasion of their 'space'. They report a positive and significant relationship between an induced oxidative stress status and two measures of aggressivity - (a) latency time to the first attack by the resident on the intruder and, (b) the number of attacks performed in five minute observation period.

correlated with certain sorts of confrontational behavior, this would provide suggestive evidence consistent with our hypothesis. In a similar vein, in US-based studies Rotton and Frey (1985) link air quality variations with psychiatric-related 911-calls, finding a significant positive correlation between psychiatric emergency calls and photochemical oxidants in Dayton, Ohio for the period 1975 and 1977.

In a more recent work, Yang et al. (2011) use monthly data to investigate the temporal pattern of suicides in the city of Taipei between 1991 and 2008. They find that after controlling for weather and unemployment, variations in ambient ozone levels explain roughly 23% of variation in the number of suicides with a particularly pronounced effect on cases of suicide by violent methods.

3 Data

The analysis in this paper uses daily data on crime, air quality and weather within Los Angeles county for the nine-year period from January 2005 to December 2013.

3.1 Crime

We use daily reported crime data as collected by 60 Federal Bureau of Investigation (FBI) law enforcement agencies within Los Angeles county. These agencies police 40 incorporated cities and the entire unincorporated county area which cover 423 zip codes within LA county. The data-set covers 30 different types of crime following nationally-recognized FBI definitions. The definition for simple assault, aggravated assault and larceny are presented in Table 1.

The daily reported number of crimes are obtained from the Los Angeles County Sheriff's Department (LASD).[10] For each reported crime, the data-set provides incident date, reported date and location as both a full address (the street number, street name and zip code) and geocode coordinates. Incident date is used for this study since we are interested in date a crime is committed.[11] The location is also classified categorically by police administrative area as defined by the LASD.

Given the biological research linking ozone to aggression, aggressive-defence, *etc.,* we focus on violent crime, in particular assaults. To build a time series for daily number of assaults, we first drop those agencies that reported fewer than 12 months of data for any

[10]This data is available at http://shq.lasdnews.net/CrimeStats/LASDCrimeInfo.html.

[11]We had initial concerns about some incidents where there was a discrepancy between the incident and report dates. In private communication, the LASD confirmed that in the vast majority of cases (more than 99%) the date of the incident is known with certainty, most often through the records of an attending officer. To ensure robustness, we re-estimated our preferred specifications excluding those incidents where the report date and incident date differed, with little impact on results.

specific year are dropped for that year.[12] We then drop all crimes that are gang-related.[13] A composite index for assaults is constructed that sums aggravated and non-aggravated assaults by all remaining agencies for each incident date. A feel for the seasonal variability in crime incidents is provided in Figure 1. The upper panel presents the monthly average number of assaults, and the bottom panel shows monthly average number of burglaries (which we will later use as a robustness check). Assaults are concentrated in the hotter, more polluted months of May to August while the burglaries are more up-and-down through the year.

Crime data typically has a number of shortcomings. We only have data on *reported* crime. This is a perennial problem in research in this area and there is little we can do about it. Surveys of experience of crime - such as those conducted by the United States Department of Justice - ask respondents if they have been victims of crime over a period of time but is not available at the daily level. They also pose data-reliability challenges of their own. In addition, reported incidents may on occasion be mis-categorized due to the police error. We do not expect this to affect the consistency of our estimates as there is no reason to suspect that the prevalence of recording errors would be correlated with pollution levels (Hausman (2001)).

3.2 Air quality and weather

The South Coast Air Quality Management District (SCAQMD) is the air pollution control agency for all of Orange County and the urban portions of Los Angeles, Riverside and San Bernardino counties, and is one of the smoggiest regions of the United States. To control for weather and co-pollutants factors, we employ daily measures of ozone (O_3), carbon monoxide (CO) and nitrogen dioxide (NO_2) levels. Pollution data are obtained from the California Environmental Protection Agency Air Resources Board.[14] In our analysis, we focus on the possible effect of ozone for two reasons: (1) the biological literature places particular focus on mechanism whereby higher exposure to ozone increases the levels of aggressivity, impulsivity, loss of control *etc.* in animals and humans; and (2) ozone is a major pollutant - with considerable daily spatial variation - within Los Angeles county, and widely-used as a generic measure of air quality.

To allow us to control for the weather confounders in the main regression we col-

[12] There remain 53 unbalanced agencies for each year for the period of 2005 - 2013.

[13] The gang-related categorization is adjudged by the attending officer. Los Angeles is host to a significant level of gang violence and it is possible that the process driving gang-violence is different from those that drive the non-gang-related events. Gang-related assaults might, for example, be more premeditated or more group-determined, in which case the loss-of-control model motivated by the literature review may be less applicable. Less than 5% of all assaults in our dataset are gang-related. For completeness we re-estimate our main specifications including gang-related incidents with no substantive difference to the results.

[14] This data is available at http://www.arb.ca.gov/aqd/aqdcd/aqdcddld.htm.

lect daily measures for maximum temperature, minimum temperature, average wind speed, precipitation, humidity and cloud cover from sunrise to sunset from the *Surface Summary of the Day* database which is maintained by the National Climate Data Center (USNCDC). Therefore in addition to linear weather regressions we include series of temperature and dew point temperature indicator variables (bins) for every 3 degrees Fahrenheit.[15] Also included are interaction terms between each temperature and dew point indicator.[16] Weather and pollution data are assigned to each crime location based on the closest pollution monitoring and weather stations using the zip code for each reported crime.[17] We then compute the average level of these variables over all zip codes for each law enforcement agency.[18]

Table 2 provides summary statistics. To show a suggestive correlation between ozone levels and assaults, Figure 2 plots daily patterns of ozone levels and daily number of assaults during a month (July 2011). There is an evident of co-movement between these series. Such "eye-balling" is only suggestive since there are a number of other cofounders for which we need to control.

To address endogeneity in pollution exposure, measurement error and omitted variable concerns, we use wind direction as an instrumental variable for ozone levels. Wind direction data is collected from National Climatic Data, which are maintained by the National Oceanic and Atmospheric Administration (NOAA).

4 Methodological challenges

Estimating a causal relationship between ozone exposure and assault, consistent with the various strands of biological research outlined, throws up a number of challenges.

First, concerns arise about the potential endogeniety in individuals' exposure to pollution. In the short-run people may engage in avoidance behavior to mitigate their pollution exposure, for instance by spending more time indoors (Neidell (2009)). In the long-run, non-random pollution exposure can arise from residential sorting (Chay and Greenstone (2005)).

[15] As indicated by Zivin and Neidell (2012), dew point temperature can be used as a measure of absolute humidity.

[16] It is important to emphasize that all linear weather regressions include the quadratic temperature term as a weather control. The impact of temperature on crime is shown to be approximately U-shape. The weather data is available at: http://www.ncdc.noaa.gov/cdo-web/datasets.

[17] Los Angeles county includes 60 law enforcement agencies, 423 zip codes, 20 pollution monitoring and 30 weather stations.

[18] Assigning pollution from monitors to individuals in the literature of health impacts of pollution is a debated issue. Although, assigning pollution to each reported crime at the zip code level can enhance accuracy, it may increase measurement error if people travel beyond their zip code. We re-ran all of our regressions using two alternative pollution measures constructed by (1) calculating a daily, across-station air quality average and (2) assigning the closest pollution monitoring values to each law enforcement agency. The results are not reported here but coincide in sign and significance.

Second, there are various potential sources of measurement error. Principal amongst these is that the underlying mechanisms point to the importance of ozone *exposure* being what matters whereas we have only a proxy for that - namely the average level of pollution in a zip code on a given day. An individual's exposure depends on where they have been in the course of the day - since pollution levels vary across locations in the city - while we only know where they are at the moment that the crime is committed.

A third concern is the potential for bias due to omitted variables. This could arise due to difficulty in fully control for weather and other environmental confounders. Other potential omitted variables include alcohol consumption which can itself be expected to be influenced by weather conditions.

5 Empirical approach

To address the challenges just noted we - in addition to OLS - 2SLS to estimate the following:[19]

$$\log(assault)_{ft} = \beta_0 + \beta_1 ozone_{ft} + W_{ft}\beta_2 + P_{ft}\beta_3 + \Phi_f + \phi_t + \epsilon_{ft} \tag{1}$$

$$\begin{aligned} ozone_{ft} = \gamma_0 + \gamma_1 west_{ft} + W_{ft}\gamma_2 \\ + P_{ft}\gamma_3 + \psi_t + \Psi_f + \upsilon_{ft} \end{aligned} \tag{2}$$

Equation (1) is the second-stage and Equation (2) is the first-stage regression. The dependent variable $log(assault)_{ft}$ is the natural logarithm of the aggregate number of assaults recorded at law enforcement agency f committed on day t.[20] Focusing on the aggregate daily number of assaults as a measure of violent crime provides several advantages. Assault is easily the most prevalent category of violent crime in Los Angeles - there are around 34 reported assaults each day for the period of our study. This high daily frequency of assault offers greater statistical reliability, allowing us to study significant variations in pollutant levels and weather factors. Moreover, unlike other violent crimes such as manslaughter or rape, assaults tend to be reported and recorded immediately and revealed less cautiously.

Our independent variable of interest $ozone_{ft}$ is the daily mean of one-hour ozone level (in parts per million) on date t at law enforcement agency f. To be able to derive precise estimates we need considerable variation in measured ozone after controlling for seasonality, zip code, weather and other co-pollutants. Figure 3 shows this to be the

[19] We also estimated the single-equation variant using Poisson maximum likelihood (Cameron and Trivedi (2013)). The results proved very close to the OLS estimates and we do not report.

[20] By specifying our dependent variable as a level rather than rate (i.e., crime per 10 000 of population) we are consistent with previous studies on health impacts of ozone. This is also consistent with other studies that use incident-based crime data such as Card and Dahl (2011) and Jacob et al. (2007).

case; plotting the daily residual in one-hour ozone after controlling for seasonality, zip code, weather and other co-pollutants. This residual variation provides the basis for identification in the paper.

One concern with using daily variation in ground level ozone is that weather and other co-pollutants have direct impacts on assaults and we may fail to control properly for their effects (Neidell (2009)). Regarding weather confounders, the vector W_{ft} includes a set of weather controls, namely; maximum temperature, quadratic maximum temperature, minimum temperature, precipitation, average relative humidity, average cloud cover and average wind speed. As discussed, to control flexibly for the two main meteorological precursors of ozone formation, namely temperature and sun light, we include a series of temperature and dew point temperature indicator variables for every 3 degrees Fahrenheit. Also included are interactions of every temperature indicators with cloud cover.[21]

In terms of co-pollutants, if other pollutants' exposure causes violent behavior, ignoring them could lead us to *under*-estimate the impacts of ozone pollution. The vector P_{ft} includes controls for other co-pollutant variables that may have an independent effect on assaults and contains the daily mean of one-hour nitrogen dioxide (NO_2) and eight-hour carbon monoxide (CO).[22] However, the estimated coefficients of interest prove insensitive to the exclusion of this pair of controls, assuaging concerns that they play an important confounding role.[23]

Φ_f and ϕ_t are location and time fixed effects, respectively. We use law enforcement agency fixed effects Φ_f to control for unobservable factors within an agency that influence crime but are not correlated with air pollution (*e.g.* local average crime rate, existence of a homeless shelter). ϕ_t includes day of week and holiday dummies to account for changes in activities and year-month dummies to capture both seasonal and temporal trends in pollution and crime patterns. Following Foley (2011) we also control for the potential effect of welfare payments on crime[24] There are three primary welfare payments - Food Stamps, the Temporary Assistance for Needy Families (TANF), and payments under the Supplemental Security Income (SSI) program. In Los Angeles SSI and TANF

[21] There is an established literature relating crime to weather conditions (Cohn (1990), Jacob et al. (2007), Horrocks and Menclova (2011) and Ranson (2014)) and our choices have been informed by this.

[22] This analysis does not incorporate particulate matter (i.e., $PM_{2.5}$ and PM_{10}) since it is not measured on a daily basis. We address concerns about omitted variable bias by running a robustness check in which we exclude all non-ozone pollution controls, however, results shown to be insensitive to exclusion of co-pollutants.

[23] We also re-estimated our key specifications using Air Quality Index (AQI) instead of ozone, arriving at very similar results (in all cases the sign and significance of key coefficients remained unchanged).The AQI is a widely used composite measure of air quality based on six criteria pollutants (ozone, carbon monoxide, particulate matter, nitrogen dioxide, lead and sulfur dioxide). The USEPA requires local jurisdictions to collate and publish AQI data in a standardized format. We contemplated basing the paper on AQI but ultimately preferred to focus on ozone because of the primacy attributed to it in the biological literature reviewed earlier.

[24] Several studies suggest that benefit payments have a short-run (same day) influence on crime (Corman et al. (2014), Wright et al. (2014) and Foley (2011)).

programs make payments to recipients on the first working day of each month. Food stamp payments occur during the first and second weeks of the month, with the date of distribution depending on the last digit of the recipient's case number. As such, ϕ_t also includes a dummy that takes the value 1 in the first 15 days of each month and zero otherwise

Figure 4 provides an indication of the seasonal variation of pollution levels in Los Angeles. Ozone exhibits a strong seasonal pattern, with higher levels in summer. CO and NO_2 the reverse.

5.1 First-stage regression: Wind direction as an instrument

Ozone in Equation (1) is instrumented using W/WSW winds. $west_{ft}$ in Equation (2) is a dummy variable that takes the value one when the average wind direction at location f on day t is blowing from the west or west-south-west and zero otherwise.[25] There are a number of characteristics that make wind direction an attractive candidate as an instrument in this context.

The influence of wind direction on ozone levels in LA - in particular westerly winds worsening air quality - is well-recognized (Witz and Moore Jr (1981), Westerdahl et al. (2008), Yu et al. (2004), Jacobson (2005), Kim et al. (2002) and Hudda et al. (2014)). The LA basin has particular topography - it sits on the United States west coast with higher land (the Angeles and San Bernardino National Forests) and associated mountains with 11 000 foot peaks to its east and north-east. W/WSW winds carry volatile organic compounds and oxides of nitrogen over inland areas. In the presence of sunlight and because of relatively low levels of rain and wind speed, transported and locally-arising pollutants become ozone which is trapped by the mountains (Westerdahl et al. (2008), Yu et al. (2004), Choi et al. (2013) and Kozawa et al. (2009)). Lu and Turco (1994) provide a discussion of the interaction between sea breezes and topography of the LA basin on the production of high level of ozone, with the key factor being the W/WSW winds which hold the polluted air mass over the city against the 'cushion' of high-land.

The detrimental impact of W/WSW wind is exacerbated by (but does not rely on) the location of the Ports of Los Angeles and Long Beach to the south-west and Los Angeles International Airport (LAX) to the west. The Ports of Los Angeles and Long Beach combined are the two largest and busiest ports in the United States and LAX is the third busiest airport in the United States. LAX is estimated to be the largest point source of CO and the third largest of NO_x emissions in the Los Angeles county (EPA, 2005) while port activities contribute about 25% of total NO_x emissions in the Los Angeles

[25] This study defines west as the compass conduct between 240° and 275°. The average wind direction at coastal area is 252° which is west-south-west. West/west-south-westerly (W/WSW) onshore winds are the most common local winds in the Los Angeles basin - a factor that plays a significant role in the generally poor standard levels of air quality in the city.

area (AQMD, 2003).

The following one-sentence summary bears repeating;

> "The Los Angeles basin is unfortunately uniquely suited to ozone pollution. It's a combination of the ring of mountains, wind direction and lots of sources upwind that produces the high ozone" (Suzanne Paulsen, Director of the UCLA Center for Clean Air, 2014).

Figure 6 provides context. The map shows the study area, including the locations of LAX and the Port of Los Angeles, with arrows added to capture the W/WSW wind. The picture in the lower panel, taken from the south-west, emphasizes the proximity and stature of the cushion of mountains. Subsequent sections will establish statistically the impact of westerly winds on ozone.[26]

Daily variation in wind direction can plausibly then be treated as exogenous and uncorrelated with other short-run determinants of criminal behavior. In the upper atmosphere wind directions vary with large-scale weather systems and resulting changes in pressure patterns. Local variations in wind can result from differences in temperature and pressure in smaller areas. While we control flexibly for the effects of air pressure and temperature - the two most important meteorological determinants of wind patterns - there remains significant unexplained and unpredictable variation in wind direction.

Validity of the instrument requires that there be no direct link from wind direction to criminal behavior once other weather characteristics are controlled for. It is difficult to think of any such link. In a review of the extensive literature on the effect of weather on crime we find no reference to the possibility that wind direction impacts any category of crime.[27] There are four studies that seek to investigate the effect of wind *speed* - arriving at mixed (and weak) results - while no study points to any role for wind direction.[28]

6 Results

6.1 OLS

Table 3 presents OLS results from estimating Equation (1). The four Columns of Table 3 reflect estimation with alternative combinations of controls. The specification in Column

[26]Statistically the instrument proves very strong, delivering F-statistics in the base specifications in the range of 130 to 170, against the usual rule-of-thumb of 10.

[27]In contrast, other weather variables (especially air temperature and precipitation) are influential. For a few examples amongst many that are specific to assault see Cohn and Rotton (1997) and Ranson (2014).

[28]It is just about possible to contrive a story that might link wind *speed* to criminal behavior. The studies that incorporate wind speed are Rotton and Frey (1985), Rotton and Cohn (2000), Miller (1968) and Horrocks and Menclova (2011). For completeness, we control for possible effects of wind speed by including average wind speeds in our main regressions. Dropping wind speed has no impact on results.

(1) is linear and includes controls for weather and pollution covariates, as well as agency and time fixed effects (day of week, holiday and year-month). The coefficient of interest is that on ozone and equal to 3.133 which is statistically significant at the 0.01% level. The interpretation of that coefficient is straight-forward - other things equal- a 10 ppb increase in ground-level ozone concentration on a particular day is associated with a 3.1% increase in the daily number of assaults.

Columns (2) and (3) exclude co-pollutants and weather covariates in turn.[29] The estimated coefficients remain quite stable across the three specifications - exclusion of weather and co-pollutants controls has only a minor impact, changing the coefficient from 3.13 to 3.09 and 3.13. In each case the role of ozone has the expected sign and is significant at the 1% level. The stability of the estimate when the co-pollutant controls are dropped (Column (3)) allays concerns that by focussing on ozone as our air quality measure of interest we may be missing confounding action through the effects of other pollutants. Insofar as that is a problem, it seems to be a small one.

It is important to note that this study assumes a linear relation between incident of an assault and ozone concentration. However, to allow for a nonlinear effect of ozone, following Zivin and Neidell (2012), we estimate our OLS model by including indicators for every 4 ppb of ozone. As shown in Figure 5, there is a relatively linear increase in the point estimate effect of ozone over the entire range of ozone. Interestingly the impacts become statistically significant at 38 - 42 ppb, well inside the current ozone standard of 75 ppb.

Columns (4) - (6) present the results of checks for robustness to two different types of re-specification. First, the possibility of non-linear impacts of ozone concentrations on assault is also examined by including the quadratic form of ozone into regression. The impact proves statistically significant, and the reader can see that the estimated coefficient on ozone changes only slightly (the 3.13 in Column (1) becomes 3.62 in Column (4)).

Columns (5) and (6) include a 1-day and a 2-day lag of environmental variables to allow for the possibility of lagged effects of ozone on assaults.[30] It can be seen that the coefficients on lagged ozone levels are small and never statistically significant. This is consistent with the biological evidence that ozone exposure has an immediate and short-lived impact on behavior.

[29]Following Neidell (2009), we do not exclude maximum temperature and cloud cover since they are the two main factors of ozone formation.

[30]In fact we included lags up to 7-days of environmental variables with little impact on the results. Space precludes the presentation of the many of the alternative variants that we estimated.

6.2 IV

6.2.1 First-stage: Wind direction and air quality

Panel A of Table 4 reports the first stage estimates (Equation 2). The impact of wind direction on ambient ozone is highly significant and in each case has the expected sign. This confirms what is already well-known to those who study air quality in Los Angeles. The estimates in Column (1) indicate that a wind blowing from the west increases ozone levels in the immediate area by 7 ppb.

In Panel C we report F-statistics from first-stage. Across all five specifications (with varying batteries of controls) the instrument is strong, with the F-statistic ranging from 38 to 139 against a conventional benchmark of 10.

6.2.2 Second-stage: Air quality and crime

Table 4 reports the results of IV estimation. Methodological concerns already outlined in Section 4 point to IV method having potential to be a more secure estimation method than OLS in this setting.

The second-stage results are reported in Panel B. Column (1) is the linear specification with a full suite of controls. The estimated coefficient on ozone - our coefficient of interest - is positive and significant at the 1% level. According to this specification a 10 ppb increase in ozone levels causes a 19.4% increase in the same-day assaults.

The Wu-Hausman test indicates that the difference between the OLS and IV estimates is statistically significant with a p-value below 0.05 for all specifications (and in most cases below 0.01). That the IV estimates are larger is consistent with classical measurement error in ozone exposure which leads to attenuation bias in the OLS estimates (Griliches and Hausman (1986)).

Columns (2) and (3) omit weather and co-pollutants controls, respectively. Weather is known to have a significant influence on the occurrences of both violent and non-violent crimes. The estimates in Columns (2) and (3) point to the strength of the instruments in controlling for potential omitted variable bias from environmental factors, since our estimates are comparatively insensitive to the exclusion of environmental confounders. In all cases the estimates on the coefficient of interest remain positive and highly significant, though the implied 19.4% change in assaults per 10 ppb change in ozone concentrations becomes 23.2% and 20.4% in the two cases respectively.

In Columns (4) and (5) we test for the possibility of lagged effects. The lagged ozone terms are also instrumented by lagged westerly wind. Consistent with OLS estimates, neither 1-day nor 2-day lagged ozone is found to be significant. There is no evidence that ozone might have a lagged effect on assault patterns.

Taken as a whole, the results in Table 4 point to a significant positive effect of ozone exposure on the prevalence of assaults, with IV delivering higher coefficient estimates than OLS as expected.[31]

To get a sense of what this coefficient means we can interact the estimated coefficient with the distribution of ozone-levels by day in the city. Assuming the specification in Column (1), if an average bottom quartile day (in terms of ambient ozone levels with average level of 20.6 ppb) is hypothetically turned into a typical top quartile day (with average ozone level of 50.1 ppb) there is a 57% increase in the daily number of assaults.

6.3 Economic costs: Back-of-the-envelope calculation

The regressions point consistently to a significant - and in percentage terms substantial - impact of elevated ozone levels on incidents of assault. But how economically important are these numbers? The social cost of urban air pollution likely includes a variety of elements, most obviously the negative impacts on health. But how big are the crime costs?

The central IV estimates (Column (1) in Table 4) show that hypothetically moving an average cleanest quartile day (in terms of ground-level ozone concentrations) to the dirtiest quartile would be associated with a 57% increase in reported daily number of assaults. This corresponds to roughly 14 extra *reported* assaults that day across the study area. OLS variants are significantly smaller.

Under-reporting is a significant problem with crime data in the US and elsewhere. The data used here refers to reported crime, collected under the FBI's Uniform Crime Reporting Program. Since 1973 the US Department of Justice has also conducted a periodic survey to estimate prevalence of crime - the National Crime Victimization Survey (NCVS) - involving the interview of a nationally representative sample of about 160,000 people aged over 12 regarding their experience of crime (US Department of Justice (2013)). Though there are statistical and other challenges, the disparity between the numbers of assaults implied by a scaling-up of NCVS answers and crime reports has been taken as an indicator of under-reporting. The rate of under-reporting can be expected to vary across location and category of crime but Levitt (2004) contends that nationally between 33 and 50% of assaults are reported. On that basis the 14 extra reported assaults from our thought experiment would correspond to an extra 25 to 35 assaults actually taking place.

Putting a dollar value to an average assault is a challenging task. McCollister et al. (2010) put the pecuniary cost of an assault at about 19 000 USD, comprising a mixture of victim costs, justice system costs *etc.,* ignoring distress. In a contingent valuation study in the United Kingdom Atkinson et al. (2005) estimate the willingness to pay to avoid an

[31] For completeness in Table A1 in the "Appendix for Referees" we report point estimates for all covariates.

assault (no injury) and an assault (moderate injury) to be 5 300 GBP and 31 000 GBP, respectively. Cohen et al. (2004) estimate the US willingness to pay to avoid a serious assault at 70 000 USD.

Taking as conservative, the social cost of an assault being 25 000 USD, the 25 to 35 assaults therefore imply a social cost of converting a single dirtiest quartile air quality day to the cleanest quartile- in terms of impact on assault - to be in the range of 0.65 to 0.85 million USD.

7 Robustness

We believe that our methods provide compelling evidence of a causal link between air pollution and violent crime levels. However for completeness we are keen to challenge its robustness in a number of ways.

Tables 3 and 4 established robustness in sign and significance of the estimated impact across various alternative specifications (alternative controls, lagged effects, etc.) both within and between OLS and IV methods. Further, the size of the estimated coefficients has proven comparatively stable. In the following section we report some more robustness checks.

7.1 Falsification: violent vs. non-violent crime

Experimental and other research from other disciplines points to exposure to air pollution impacting the emotional and behavioral state of humans (and animals). In particular, reduced air quality is associated with increased aggressivity, impulsivity, irritability and loss of inhibition/self-control.

It is apparent that this should impact various *types* of crime differently. A stylized "road rage" incident, for example, involves loss of temper. This sort of behavior - momentary, unpremeditated and emotionally-charged - implies a loss of control that we would expect to be sensitive to the sorts of pollution-induced emotional and mood changes central to the literature review. At the other end of the spectrum crimes such as larceny, burglary, fraud or cheque forgery are much less impulsive and more likely to be planned and scheduled in advance. In particular, the stealing of any property or article such as thefts of bicycles, accessories, motor vehicle parts and etc. that *is not taken by force and violence* is defined as larceny by FBI (these are the exmaples listed on the FBI website). As such, we would not expect them to be susceptible in the same way.

We have already presented our analysis for the most prevalent class of violent crime - assault. In this subsection, we repeat the exercise for the most prevalent class of non-violent crime, namely larceny-theft. Our hypothesis is that variation in ozone will not significantly influence the pattern of larcenies.

Table 5 contains the results from OLS and IV estimation with natural logarithm of daily number of larcenies as the dependent variable under a pared down set of specifications. The IV is estimated with a full set of controls and also with the weather and co-pollutant controls excluded in turn.[32] Looking at Panel B we can observe that the estimated coefficient on ozone varies in sign across the specifications (three positive, two negative) and is never significant even at the 10% level. This supports out hypothesis that exposure to ozone induces an increase in violent but not non-violent crime.

7.2 External validity: Houston

Perhaps there is something particular about Los Angeles (or California) that makes the results setting-specific?

To investigate this possibility we repeat the analysis for Houston. This can provide meaningful out-of-sample corroboration. Houston is a city of around 2.2 million inhabitants, located 2,210 km east-southeast of Los Angeles. It is subject to different weather and air pollution systems and, being in a different state (Texas) with different socio-economic profiles and subject to different law enforcement practices, *etc.* The rates per capita of all categories of violent crime are substantially higher in Houston than Los Angeles, but that does not matter for current purposes given our focus on daily variations.

The results based on OLS and IV estimation are reported in Table 6.[33] As shown in Panel C, wind direction remains a strong instrument, delivering a F-statistic over 15.3. We can observe that the coefficient on ozone in Panel B is positive and significant at the 1% level for each specification. The values are also similar in terms of order of magnitude to those from the LA analysis, and again the IV estimates are substantially higher than OLS. Concentrating on the IV specification the estimated coefficient on same-day ozone is 9.51 compared to 19.37 in the corresponding specification for LA.

To complete the set, we also re-estimated the regressions with larceny rather than assault as the dependent variable and corroborated qualitatively the LA results from Section 7.1 (ozone had no significant impact on incidents of larceny). The detailed results are not reported here.

[32] In fact we tried a much richer variety of specifications and the qualitative results were sustained. We only report the five basic variants here to save space.

[33] The change in geography implies that while we continue to use wind direction as our primary instrument, it is now winds from the *south-east* - coming off the Gulf of Mexico - that have the most important influence on air quality. In particular, the topography of the area means that south-easterly winds have a cleansing effect on Houston air. Therefore our instrument variable in this cases is a dummy variable indicating when wind is breezing from the southeast (defined as coming from a compass point between 112.5° and 157.5°.)

7.3 Placebos

Recent debates regarding causal inference in the social sciences have led to a desire for "tests of design" (Hartman and Hidalgo (2011)). In the design-based inference literature, they serve to address concerns that the research design may *itself* be tending to generate an apparent causal effect.

The most common class of such tests is placebo tests, which examine the effect of an alternative (or placebo) series known to be unrelated either by design or substantive theory. The placebo series - by construction - should have no explanatory power. If this is not the case then the validity of the research design is called into question.

Returning to the Los Angeles case and following Lavy et al. (2014), we use three different placebo independent variables, one pre-treatment, one post-treatment and one the concentration level of ozone in New York, a city 2800 miles east-north-east of Los Angeles. In particular our preferred OLS and IV specifications were re-estimated with same-day ozone replaced as an explanatory variable by the ozone level recorded 100 calendar day *before* the date in question, 100 calendar day *after*, and the daily-average ozone concentrations in New York.

The results of this exercise are summarized in Table 7. Estimated coefficients are mixed in sign and much smaller than those in the table of main estimates. In no case does the coefficient come close to significance at the 10% level.

8 Conclusion

The health costs of air pollution are well-recognized and motivate policies designed to improve air quality.

However, exposure to common air pollutants can also be expected to impact a much wider set of economic and social outcomes. Introspection suggests that short-term exposure to pollution can change the way we feel and behave - it might make us irritable or less able to concentrate. Consistent with this recent research provides evidence of causal links from day-to-day variations in air quality to outcomes such as workplace productivity (Zivin and Neidell (2012)) and human capital accumulation (Lavy et al. (2014)). Failure to account for these additional effects relative to the social benefits of clean air can be expected to bias policy outcomes in favour of excessively lax standards.

Ethologists have for many years known that exposing animals to common air pollutants (including but not limited to ozone) increases their propensity for aggressive behavior. A careful reading of that research motivated this study of the impact of ozone on violent crime.

Consistent with the science we identify a highly significant and independent effect of ground level of ozone on the incidence of criminal assaults in Los Angeles. The estimated impact of ozone on assaults coefficient is always positive and highly significant across a wide range of different estimation methods and specifications (*e.g.* combinations of controls, non-linear and lagged effect). The results prove remarkably robust to a number of sensitivity and falsification tests.

The estimated effects are substantial - both in terms of percentage increases in the number of assaults and their implied monetary value. Are they plausible? The experimental literature on the impacts of ozone on animal behavior is consistent in sign and magnitude of effects of this study with the hypothesis that turning a clean air day into a dirty air day (bottom- to top-quartile) could induce an extra 20 to 30 criminal assaults in a metropolis the size of Los Angeles (of which about half would be reported).

Our future work will challenge the causal relationship between poor air quality and criminal behavior using other methods and in other settings.

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Tables

Table 1: Offense Definitions

Offense	Definition
Aggravated assault	An unlawful attack by one person upon another for the purpose of inflicting severe or aggravated bodily injury.
Non-aggravated assault	Assaults which do not involve the use of a firearm, knife, cutting instrument, or other dangerous weapon and in which the victim did not sustain serious or aggravated injuries.
Larceny-theft	The unlawful taking, carrying, leading, or riding away of property from the possession or constructive possession of another.

Source: FBI (2004).

Table 2: Summary Statistics for January 2005 - December 2013

	Mean	Std. Dev.
Number of dates	3,287	
Daily assault	24.26	10.67
Daily larceny	42.34	11.17
Explanatory Variables		
Carbon monoxide 8-h (ppm)	0.666	0.38
Ozone 8-h (ppm)	0.042	0.01
Nitrogen dioxide 1-h (ppm)	3.446	12.02
AQI	85.56	34.02
Precipitation (mm)	7.114	37.710
Maximum temperature (°C)	24.028	5.12
Minimum temperature (°C)	13.682	4.25
Humidity (percent)	81.178	11.89
Cloud cover sunrise to sunset (percent)	2.27	2.47
Wind speed (km/h)	2.54	1.59
Wind direction (degree)	206.86	92.95

Sources: Crime data from the Los Angeles County Sheriff's Department. Weather data from the US National Climatic Data Center (USNCDC). Pollution data from California Environmental Protection Agency Air Resources Board.

Table 3: OLS Estimates

	(1)	(2)	(3)	(4)	(5)	(6)
Ozone	3.133***	3.089***	3.132**	2.951***	3.217***	3.085***
	[0.625]	[0.613]	[0.633]	[0.584]	[0.673]	[0.635]
Ozone_{t-1}	-	-	-	-	-0.315	-0.175
	-	-	-	-	[0.294]	[0.07]
Ozone_{t-2}	-	-	-	-	-	-0.968
	-	-	-	-	-	[0.554]
Controls for weather	Y	N	Y	Y	Y	Y
Controls for pollution	Y	Y	N	Y	Y	Y
Time fixed effect	Y	Y	Y	Y	Y	Y
Agency fixed effect	Y	Y	Y	Y	Y	Y
Functional form in ozone	Linear	Linear	Linear	Quadratic	Linear	Linear
Observations	71,351	71,351	71,351	71,351	71,351	71,351

Notes: Dependent variable is natural log of daily number of assaults. All regressions include controls for temperature (2.5 degree F indicators), temperature (2.5 degree F indicators) × cloud cover, dew point (2.5 degree F indicators). Clustered by law enforcement agencies, standard errors are in brackets.
* significant at 5% ** significant at 1% *** significant at 0.01%.

Table 4: IV Estimates

	(1)	(2)	(3)	(4)	(5)
A.First stage [(a)]					
West	0.007***	0.006***	0.006**	0.003***	0.003***
	[0.0006]	[0.0003]	[0.0003]	[0.0003]	[0.0003]
B.Second stage [(b)]					
Ozone	19.37**	23.02***	20.46**	17.09***	22.01***
	[6.088]	[5.756]	[6.971]	[8.35]	[6.705]
Ozone_{t-1}	-	-	-	-10.21	8.17
	-	-	-	[0.004]	[0.]
Ozone_{t-2}	-	-	-	-	0.668
	-	-	-	-	[0.673]
Controls for weather	Y	N	Y	Y	Y
Controls for pollution	Y	Y	N	Y	Y
Time fixed effect	Y	Y	Y	Y	Y
Agency fixed effect	Y	Y	Y	Y	Y
Functional form	Linear	Linear	Linear	Linear	Linear
C. F statistic [(c)]	139.45	104.94	91.94	38.35	139.62
Wu-Hausman test	7.514	5.72	4.453	9.051	8.275
(P-value)	0.008	0.0167	0.0103	0.026	0.004
Observations	71,351	71,351	71,351	71,351	71,351

Notes: (a) Dependent variable is ozone. (b) Dependent variable is log(assault). (c) The values reported are the Angrist-Pischke multivariate F-statistics (Angrist and Pischke (2009)). All regressions include controls for temperature (2.5 degree F indicators), temperature (2.5 degree F indicators) × cloud cover, dew point (2.5 degree F indicators). Clustered by law enforcement agencies, standard errors are in brackets. Both lagged variables are instrumented by westerly wind, and lagged wind direction.
* significant at 5% ** significant at 1% *** significant at 0.01%.

Table 5: Falsification: Larceny

	(1)	(2)	(3)	(4)
	OLS	IV	IV	IV
A.First stage $^{(a)}$				
West	-	0.005***	0.0005**	0.0014***
	-	[0.0006]	[0.0002]	[0.0006]
B.Second stage $^{(b)}$				
Ozone	-0.429	1.47	2.13	1.37
	[0.373]	[9.122]	[34.08]	[10.50]
Controls for weather	Y	Y	N	Y
Controls for pollution	Y	Y	Y	N
Time fixed effect	Y	Y	Y	Y
Agency fixed effect	Y	Y	Y	Y
C. F statistic $^{(c)}$	-	80.13	5.15	57.05
Observations	72,458	72,458	72,458	72,458

Notes: (a) Dependent variable is ozone. (b) Dependent variable is log(larceny). (c) The values reported are the Angrist-Pischke multivariate F-statistics (Angrist and Pischke (2009)). Clustered by law enforcement agencies, standard errors are in brackets.
* significant at 5% ** significant at 1% *** significant at 0.01%.

Table 6: External Validity: Houston

	(1) OLS	(2) IV
A.First stage $^{(a)}$		
East	-	-0.005***
	-	[0.0759]
B.Second stage $^{(b)}$		
Ozone	2.26***	9.51***
	[0.129]	[2.65]
Controls for weather	Y	Y
Controls for pollution	Y	Y
Time fixed effect	Y	Y
Agency fixed effect	Y	Y
C. F statistic $^{(c)}$	-	15.34
Observations	21,937	21,937

Notes: (a) Dependent variable is ozone. (b) Dependent variable is log(assault). (c) The values reported are the Angrist-Pischke multivariate F-statistics (Angrist and Pischke (2009)).
Clustered by beats, standard errors are in brackets.
* significant at 5% ** significant at 1% *** significant at 0.01%.

Table 7: Placebo Tests Estimates

	Pre-treatment		Post-treatment		New York Level	
	(1)	(2)	(3)	(4)	(5)	(6)
	OLS	IV	OLS	IV	OLS	IV
Ozone	0.064	-6.38	0.036	9.57	0.098	-1.57
	[0.195]	[8.31]	[0.201]	[11.73]	[0.451]	[6.56]
Controls for weather	Y	Y	Y	Y	Y	Y
Controls for pollution	Y	Y	Y	Y	Y	Y
Time fixed effect	Y	Y	Y	Y	Y	Y
Agency fixed effect	Y	Y	Y	Y	Y	Y
Observations	71,351	71,351	71,351	71,351	71,351	71,351

Notes: Dependent variable is log(assault). Regressions are estimated based on Equation 1 and 2, but actual ozone level is replaced by the ozone from the 100 calendar day before and after, and ozone level in New York. Clustered by law enforcement agencies, standard errors are in brackets.* significant at 5% ** significant at 1% *** significant at 0.01%.

Figures

Figure 1: Number of Assaults and Larcenies by Month

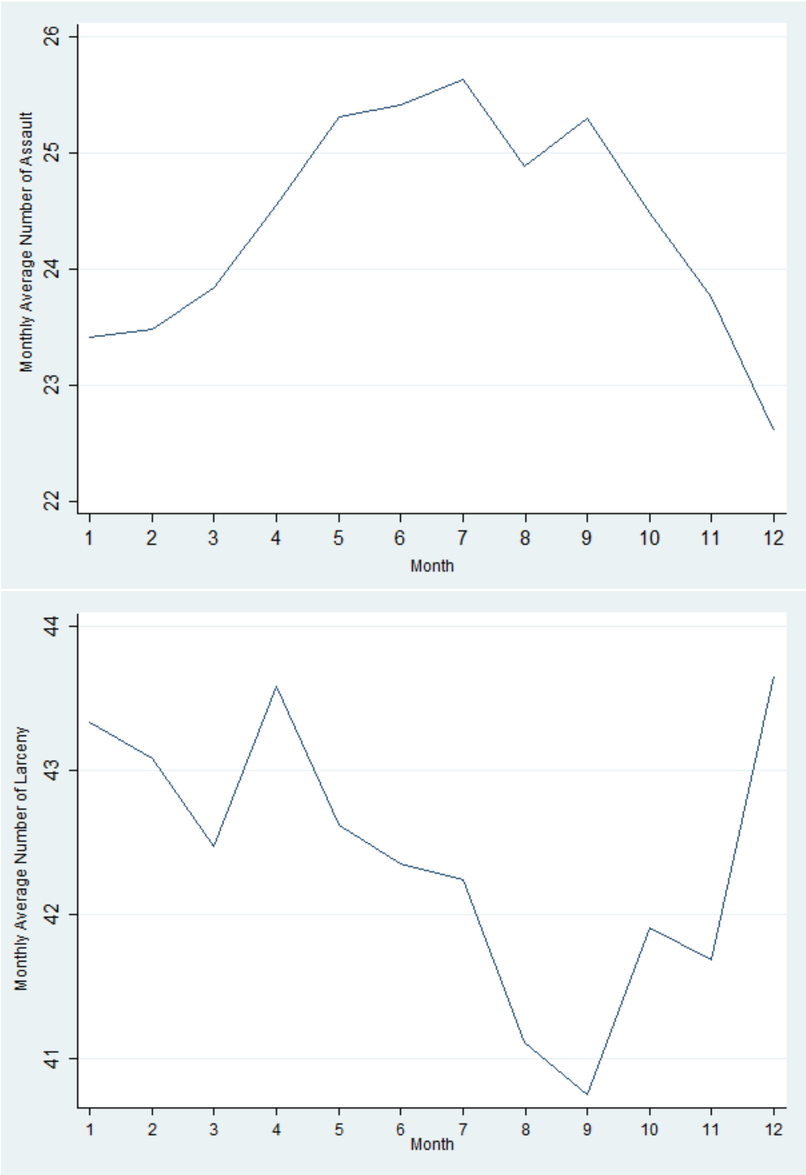


Figure 2: Daily Ozone Levels and Assault Rates During July, 2011

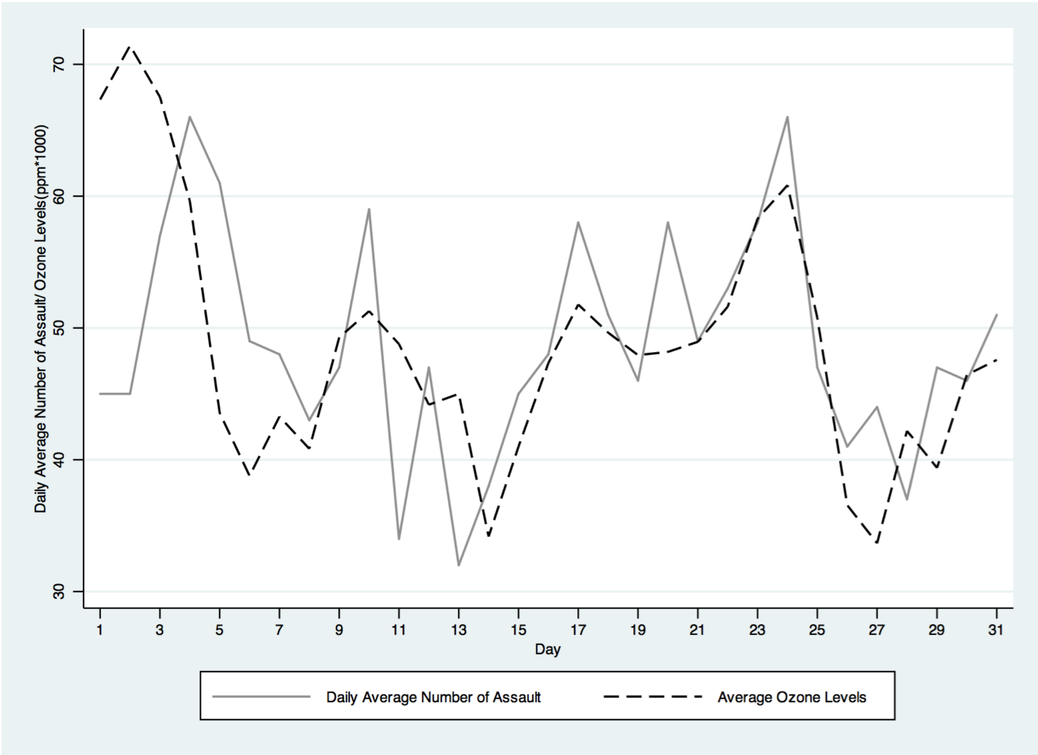
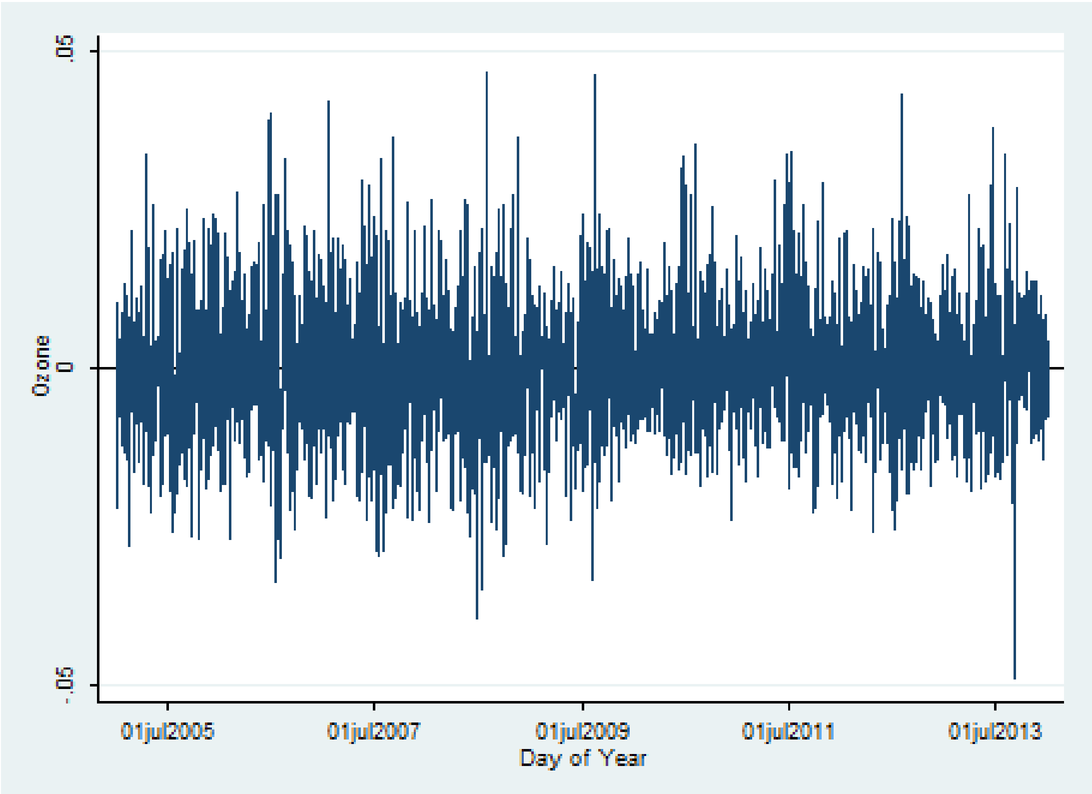


Figure 3: Daily Residual Variation in One-hour Ozone (January 2005 - December 2013)



Note: This figure plots the daily residual variation in ozone after controlling for co-pollutants, weather confounders, year-month and zip code dummies.

Figure 4: Average Levels of Ozone, CO and NO_2 by Month (January 2005 - December 2013)

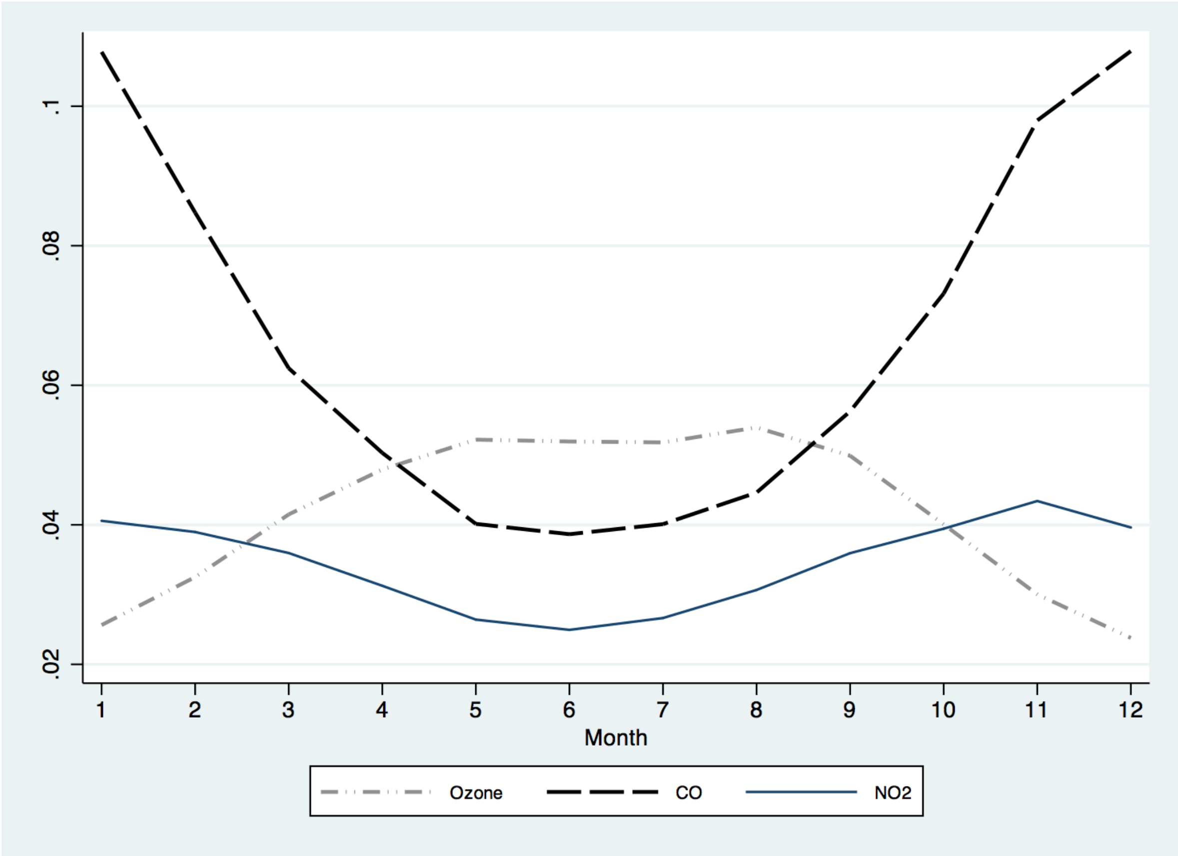
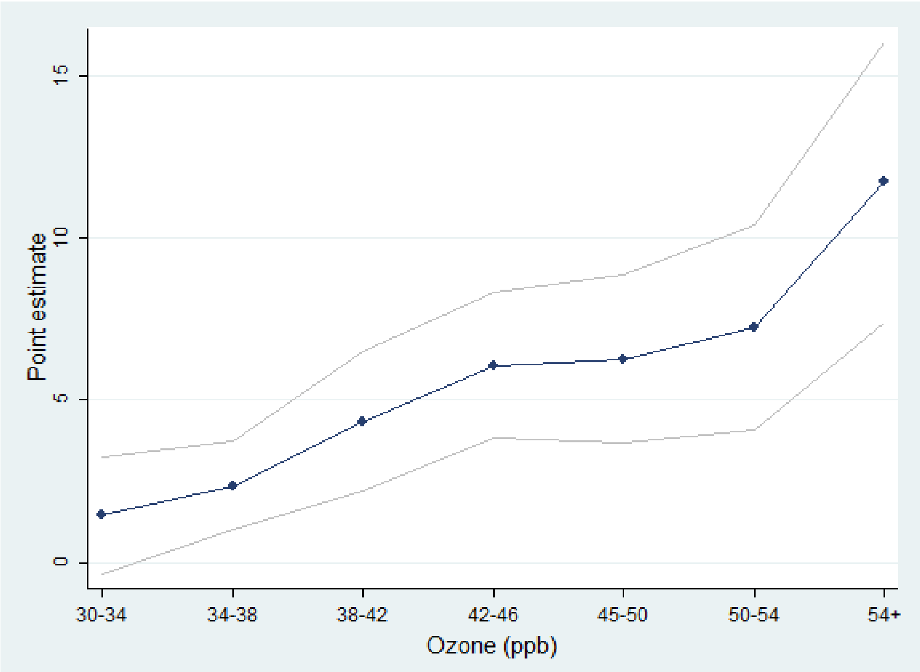


Figure 5: Regression Results of the Effect of Ozone on Daily Number of Assaults Using Flexible Controls for Ozone



Note: This figure plots the point estimates for the ozone indicator variables, with the 95 percent confidence interval based on standard errors clustered on law enforcement agency. The dependent variable is ln(daily number of assault). The regression includes controls for time, location and agency fixed effects, temperature (2.5 degree F indicators), cloud cover, temperature (2.5 degree F indicators) × cloud cover, air pressure, wind speed, dew point (2.5 degree F indicators), precipitation, CO and NO_2.

Figure 6: Los Angeles Map and Aerial Photo from the West

Referees' Appendix: Not for Publication

Table A1: Full Point Estimates of OLS and IV Regression

	(OLS)	(IV)
Ozone	3.13***	19.37***
	[0.625]	[6.09]
NO_2	-0.004***	-0.004***
	[0.0008]	[0.0004]
CO	0.07***	0.208***
	[0.016]	[0.053]
Air pressure	0.0009*	0.006***
	[0.008]	[0.000]
Wind speed	-0.008***	-0.006***
	[0.002]	[0.002]
Precipitation	-0.0009**	-0.0003
	[0.0002]	[0.0007]
Cloud cover	-0.0009	0.002
	[0.001]	[0.002]
Maximum temperature 70 -73	0.045**	0.043***
	[0.016]	[0.015]
Maximum temperature 73 - 76	0.036**	0.074***
	[0.003]	[0.019]
Maximum temperature 76 - 79	0.058*	0.083***
	[0.020]	[0.17]
Maximum temperature 79 - 82	0.116***	0.158**
	[0.038]	[0.051]
Maximum temperature 82 - 85	0.129***	0.1634**
	[0.033]	[0.074]
Maximum temperature 85 - 88	0.136***	-0.0109
	[0.065]	[0.119]
Maximum temperature + 88	0.189	-0.078**
	[0.113]	[0.035]
Time fixed effect	Y	Y
Agency fixed effect	Y	Y
Observations	71,351	71,351

Notes: Dependent variable is log(assault). All regressions include controls for temperature (2.5 degree F indicators), temperature (2.5 degree F indicators) $\times$ cloud cover, dew point (2.5 degree F indicators). Clustered by law enforcement agencies, standard errors are in brackets.
* significant at 5% ** significant at 1% *** significant at 0.01%.