ATMOSPHERIC AIR POLLUTION AND BIRTH WEIGHT

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ABSTRACT. We examine the impact of air pollution (PM10 measure) on birth weight, probability of being Low Birth Weight (less than 2500 grams), and Very Low Birth Weight (less than 1500 grams). We exploit the unique interaction between rainfall and pollution accumulation in Santiago, Chile to pin down the causal relationship between atmospheric pollution and birth outcomes. While controlling for seasonality, we find that higher rainfall leads to days with substantially less pollution, specially in the winter months. Using rainfall during various times of the gestational period as an instrument for pollution exposure, we find that atmospheric pollution (PM10) has a substantial effect on birth weight - a one standard deviation increase in pollution decreases birth weight by 125 grams. We estimate that if pollution were reduced by 1 standard deviation on average, the per cohort gains (via increased lifetime earnings) to the Chilean economy are around USD 72 million (0.04% of GDP).

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Date: April 2008.
Thanks to Michael Boozer, Adrian de la Garza, Camila Corvalan, Angela Delucia, Patrick Kline, Fabian Lange, Robert Mendelsohn, Maher Said, Tavneet Suri and participants at the Graduate Summer Workshop at Yale for helpful comments.

1. INTRODUCTION

Recent papers have debated whether birth outcomes (in particular birth weight) matter for various labor market and health outcomes. It appears that birth weight matters less for short run health outcomes (Almond et al 2005, Conley et al 2006) and more for long run labor market outcomes like income, education and development of IQ (Behrman & Rosenzweig 2004, Black et al 2007, Curie & Moretti 2007). Regardless, birth weight has been and continues to be an important measure of infant health. Infant mortality rates are significantly higher for Low Birth Weight (less than 2500 grams) and Very Low Birth Weight (less than 1500 grams) babies as compared to babies over 2500 grams (Conley et al 2005). Black et al (2007) note that government policy such as Women, Infants and Children Programs (WIC) aim at improving the nutritional intake of pregnant women hoping to affect birth weight, which in turn will result in better health of children[1].

If birth weight does matter (at least in the long run), what are the causes of lower birth weight? The literature seems settled on factors such as maternal smoking, genetic and nutritional factors and the importance of pre natal care (Kramer). One factor that is debated over is atmospheric pollution.

The epidemiological literature on the effects of outdoor (or ambient) air pollution on birth outcomes is large and finds inconclusive results. In particular Bell et al (2007) find significant effects of pollution (PM 10) on birth weight among babies born in Massachusetts and Connecticut. On the other hand various studies done in California (Salam et al 2005), Nevada (Chen et al 2002) and Northeastern United States (Maisonet et al 2001) find no significant effects of PM 10 pollution on birth weight and other outcomes[2]. International studies are also divided on the issue - Hizel & Cocksun (1998) find no effects of any PM measure of pollution on birth weight in Turkey. However, Wang et al (1997) find significant effects of pollution (measured as TSP's) on birth weight and the probability of being Low Birth Weight (LBW) in China. Studies have also been done in Lithuania, Poland, Zimbabwe, Canada, Croatia et cetera[3]. The papers in the epidemiological literature carefully control for observable characteristics, but are not able to tackle the issue of bias due to unobservables. Our paper is a contribution to the epidemiological literature on air pollution and birth weight in that it takes omitted variables bias seriously.

In the economics literature, few papers have looked at the causal link between atmospheric air pollution and birth outcomes. Notably, Chay & Greenstone (2005) examine the effect of the reduction in pollution due to the Clean Air Act of 1970 on infant mortality. While they examine birth weight as an outcome as well, they do not find statistically significant effects. Jayachandran (2006) finds large effects on infant mortality due to smoke caused by the Indonesian wildfires, but does not look at birth weight.

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[1] Almond et al 2005 have a nice literature review on policies targeted towards reducing the incidence of low birth weight (LBW)

[2] Bell et al (2007) include a nice summary of papers that try to find an effect of pollution on birth weight in the US

[3] Get these papers from Bell et al 2007

Our paper focuses on pollution and its link to birth weight. We use an instrumental variables technique to pin down the causal effect of pollution on birth weight. We find that rainfall has a strong diluting effect on atmospheric air pollution - a rainy day cuts air pollution by as much as 90% for that day and the next few days (See Figure 3). Using rainfall during the gestation period as an instrument for potentially endogenous exposure to air pollution, we are able to precisely estimate the effects of air pollution on birth weight. Moreover, we control for seasonality to ensure that our results are not driven by aggregate seasonal effects (which have been known in the epidemiological literature to impact birth weight).

Our area of study, Santiago, Chile makes this study highly relevant for policy implications - Santiago is one of the most polluted urban areas in the world (Hewitt et al, 2003)). A great deal of Chilean domestic policy concerns battling the burgeoning pollution problem[4]. In June 1996, Santiago was officially declared as a "saturated" zone for four atmospheric pollutants (Montero et al, 2002), including PM10 (which is the measure we use throughout this paper). While researchers have examined the impact of pollution on health outcomes like adult mortality and child respiratory problems in Santiago (Ostro et al 1996, 1999), to our knowledge, this paper is the first to examine the issue of birth weight in Santiago, Chile.

Unlike other developing economies, the main source of pollution in Santiago is atmospheric pollution, not indoor air pollution. Given the urban setting the use of firewood and coal for cooking is extremely rare - Adonis and Gil (2001) report that even in the *poorest* region of Santiago, only 14% use firewood or coal, while an equal percentage use gas (cleanest cooking fuel), and the remainder use kerosene. From the 2003 CASEN data[5] we note that in the relevant municipalities in our study 95% have access to natural gas as a source of cooking and heating. Only 7% of the surveyed households reported to have purchased firewood in the previous year for *any* purpose. Hence the relevant issue in Santiago is outdoor air pollution.

Our study reveals large effects of air pollution on birth weight. Moreover, the analysis reveals even larger effects on babies born to lower educated mothers. Hence, in addition to simply calibrating the effect of pollution on birth weight we underscore the importance of socioeconomic background in avoiding exposure to pollution while pregnant. Using estimates from previous papers on the gains due to birth weight we compute long term benefits due to pollution reduction. We estimate losses to the Chilean economy (due to lost wages) to be around USD 90 million per year.

2. ACCOUNTING FOR UNOBSERVABLES

In this section we outline why accounting for unobservables is important while examining the impact of pollution on birth outcomes. We assume that each household maximizes

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[4] See "Scrubbing the Skies over Chile", New York Times article by Nathaniel C. Nash, July 6th, 1992

[5] Survey of Socio-economic Characteristics of Nationals in Chile

the following utility function

$$\begin{aligned} & \max_{X,Z,P} && U(X,Y,Z) \\ (1) \qquad & \text{s.t.} && F=\sum_X Q_X\cdot X+\sum_Y Q_Y\cdot Y+\sum_P Q_P\cdot P \\ (2) \qquad & \text{where} && Y=H(Z,P,\mu) \end{aligned}$$

where F is the household's income (determined exogenously), Y represents the child's health, X represents the set of goods that affects the utility of the household, but they cannot impact health, like diamonds, P corresponds to goods that have a direct impact in the household's utility and in the health production function, for instance, exposure to pollution or number of cigarettes smoked in the house. Z represents the goods that impact directly the health production but do not enter in the utility function, for instance, schooling of the parents. Finally, μ represents household specific time invariant health endowments, like genetic factors. Q_i represents the exogenous equilibrium prices of good i.

Notice that if the researcher collects enough information, demand functions for each good can be estimated,

$$X = \mathcal{X}(F,Q,\mu) \tag{3}$$
$$Z = \mathcal{Z}(F,Q,\mu) \tag{4}$$
$$P = \mathcal{P}(F,Q,\mu) \tag{5}$$

and consequently, it is possible to obtain a reduced form for the health production function,

$$Y=\mathcal{Y}(F,Q,\mu) \tag{6}$$

Some of the literature studying health production functions have estimated equations similar to (6), however, this approach cannot really capture the restrictions implied by the model, and moreover, the notion of an underlying household health technology is lost, or information regard this technology is not provided.

Another possible estimation procedure, is based in the assumption that we can identify one mechanism of the underlying household health technology. To establish this mechanism, we have to estimate a 'hybrid' function like

$$Y=\mathcal{G}(P_k,F,Q_{-k},\mu) \tag{7}$$

where Q_{-k} represents all the prices except the price associated to P_k. This hybrid reduced form allow us to identify the direct impact of P_k in the health production function. However, one shortcoming of this approach is the possible bias due to the correlation between P_k and μ. Moreover, the correlation between μ and the determinants of the other inputs, can contaminate the estimations even further.

In order to circumvent this problem, we can use a valid instrument for P_k and avoid the bias in the estimation of the parameter or parameters associated to P_k on equation (7). In particular, the instrument $\hat{P}_k$ satisfies that the partial derivative $\frac{\partial \mu}{\partial \hat{P}_k} = 0$, and therefore we can obtain

$$\begin{aligned} \frac{\partial Y}{\partial \hat{P}_k} &= \frac{\partial \mathcal{G}}{\partial \hat{P}_k} + \frac{\partial \mathcal{G}}{\partial \mu} \cdot \frac{\partial \mu}{\partial \hat{P}_k} \\ &= \beta_{P_k} + \frac{\partial \mathcal{G}}{\partial \mu} \cdot \underbrace{\frac{\partial \mu}{\partial \hat{P}_k}}_{=0} \end{aligned} \tag{8}$$

where β_{P_k} represents the coefficient associated to P_k in the function $\mathcal{G}$, assuming that Y is additively separable on P_k.

Instrument variables strategy for the estimation of health production functions have been used in the work of Chay and Greenstone (2003). They use the Clean Air Act of 1970 as an instrument to estimate effect of pollution on the infant mortality rate. In their model, the infant mortality rate depends on level of pollution, but because omitted variables can covary with both the level of pollution and the infant mortality rate, any estimation using repeated cross sections would lead to a biased estimation of the health production function. They instrument the temporal changes on the pollution level using the Clean Air Act of 1970.

Therefore, in a more general setup, an unbiased estimation of some particular mechanism of the health production function can be achieved by measuring behaviorial components of the health production function and using instruments to capture the effect of changes of inputs that covary with the household specific endowment, or other inputs.

In our specific case, we want to examine the impact of exposure to pollution P_{ij} for a baby i, whose mother lived in municipality j during pregnancy, to birth outcomes Y_{ij}. Therefore, we estimate a equation such as

$$Y_{ij} = \beta P_{ij} + \delta \text{Prices} + \gamma \text{Income} + \phi_{ij} \tag{9}$$

where the error term ϕ_{ij} contains the specific health endowment of the family μ. In the data we do not observe prices and income, but use residential area fixed effects, year and month fixed effects as an attempt to control for these.

3. DATA

3.1. **Pollution.** Pollution data is from SEREMI de Salud (Regional Secretary of Health) in joint work with the CONAMA (National Commission of Environment). We have hourly pollution data (PM 10 concentrations) for each day between 2002 to 2005. The data is reported by monitor stations in various municipalities. Not all municipalities have monitors, hence we assign municipalities to their closest monitor to obtain pollution data for all the municipalities in Santiago. We have this data only for Santiago and its municipalities. The list of municipalities matched to their pollution station is in the Appendix. PM10 is a relevant measure of pollution as it is measures particles fine enough to be inhaled into the lungs (California EPA, 2003). Moreover, according the same agency, "PM10 is a major component of air pollution that threatens both our health and our environment".

3.2. **Birth weight and length.**

Birth weight and length data is available from the DEIS (Department of Statistics and Information of Health) which is part the Health Ministry. We have data on the population of births in all of Chile between 1990-2004. Data consists of birth weight, length, mother and father's age, mother and father's education, occupational status of mother and father, weeks of pregnancy, parity et cetera (full list of controls are in the regression tables). It contains information on municipality of residence, which is what we use to assign mothers (and hence babies) to pollution exposure in Santiago, since pollution is at the municipality level.

3.3. **Rainfall.**

We have daily rainfall data from 2000-2005. We obtained this data from Dirección Metereológica de Chile (Meteorological Secretary of Chile) which is part of the Defense Ministry. Rainfall data is available only for Santiago. Moreover, this data is obtained from one rainfall station located in Pudahuel municipality (see map of Santiago in Appendix). We assign this rainfall measure to all municipalities in Santiago. Given the size of Santiago and its municipalities (647 sq kms) this might not be too problematic.

Combined, the data we use is for Santiago from 2002-2004. We exclude the municipalities 3 out of 32 municipalities in Santiago (we discuss this in detail in the Appendix).

4. EMPIRICAL STRATEGY

Following the framework discussed in the second section, the regression we want to estimate is:

$$Y_{ij} = \beta P_{ij} + \epsilon_{ij} \tag{10}$$

Where P_{ij} is the pollution level experienced by baby i in municipality j and Y_{ij} is the birth weight of baby i in municipality j.

Our problem is that we do not observe P_{ij} - instead we have the municipality average P_j. Our specification imposes P_j on everyone living in municipality j. We can express P_j as:

$$P_j = P_{ij} + \eta_{ij} \tag{11}$$

In particular, we assume that $Cov(P_{ij}, \eta_{ij}) \neq 0$[6]. The equation we actually end up estimating is:

$$Y_{ij} = \beta P_j + \epsilon_{ij} \tag{12}$$

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[6] Notice that this is a case where the measurement error is not "classical"

The estimate we obtain from OLS is then:

$$\widehat{\beta_{OLS}} = \frac{Cov(P_j, Y_{ij})}{Var(P_j)} \tag{13}$$

$$= \frac{Cov(P_j, \beta P_{ij} + \epsilon_{ij})}{Var(P_j)} \tag{14}$$

$$= \beta \frac{Cov(P_j, P_{ij})}{Var(P_j)} + \frac{Cov(P_j, \epsilon_{ij})}{Var(P_j)} \tag{15}$$

Realize that $\widehat{\beta_{OLS}}$ is contaminated by 2 terms - a measurement error term $\frac{Cov(P_{ij},P_j)}{Var(P_j)}$ and omitted variables bias caused by $\frac{Cov(P_j,\epsilon_{ij})}{Var(P_j)}$. While the omitted variables bias is something we expected to encounter from the discussion of health production in the previous section, measurement error is a new problem.

A priori, we are tempted to believe that people who expose themselves to pollution also have characteristics that will lead to lower birth weight babies. For example, low income mothers might live in more polluted areas and have lower nutrition - both of which contribute to lower birth weight. Hence, if the true effect of pollution on birth weight is negative, then OLS will tend to overestimate the true impact via omitted variables bias. However, if there is heterogeneity in the quality of air that people breathe *within* a municipality, then the measurement error term will cause OLS to underestimate or overestimate[7]. Since both measurement error and bias are at play, it is difficult to determine before hand whether OLS overestimates or underestimates the true impact.

The omitted variable bias can be mitigated if we believe that a large part of the bias comes from residential sorting - parents that choose to live in more polluted municipalities also give birth to lower birth weight babies for reasons other than pollution exposure. We use municipality fixed effects to control for unobserved aspects of municipalities. While the fixed effect approach deals with residential sorting issues, it cannot deal with individual behavior that differs within a municipality. Moreover, even with municipality fixed effects, the problem of measurement error remains.

An instrument variable approach tackles both problems of measurement error and omitted variable bias. The instrument we use in our paper is rainfall deviations within a month.

4.1. **Rainfall as an instrument for pollution.**

There are two mechanisms by which rainfall can reduce the level of air pollution. First, through the drops of water that capture the particles floating in the air, and second, through the elimination of the thermal inversion.

Ruijgrok and Römer (1993) show that rainfall is a very efficient way to remove suspended particles from the atmosphere. In the specific case of Chile, Rubio et al. (2001), using the chemical composition of the water, prove that dew and the rainfall remove several minerals from the atmosphere, and therefore reduce the number of suspended particles in the

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[7] If $Cov(P_{ij}, \eta_{ij}) < Var(\eta_{ij})$ then measurement error plays a role of biasing β towards zero. If the condition is not held, then measurement error can bias β away from zero

air. Moreover, they show that dew formation can only can remove particles that are floating close to the ground. When a year experiences multiple episodes of rainfall, the ability of dew to remove particles is greatly reduced because the rainfall is able to clean all the different layers of polluted air. More evidence on rainfall removing suspended particles from the air comes from Dallarosa et al (2004), who study the presence of polycyclic aromatic hydrocarbons (PAH, which is a component of PM10) in the Porto Alegre, Brazil. They find a lack of PAH peaks in areas that experienced greater rainfall: "However, no PAH concentration peaks were observed at 81 Distrito station, which can be explained by a possible pollutants clean-up from the atmosphere due to rainfall, whose level at this station was twice the level reported for the other stations." (pg 8)

Cities that are surrounded by mountains very often suffer from an atmospherical phenomena called "thermal inversion". In general, air becomes cooler as it ascends; however, when a mass of warm air traps a mass of cool air underneath, the natural gradient of temperature is altered and thermal inversion is created. When this phenomena occurs in a city, the particles that naturally would be floating away from the city using the rising air current, are trapped in the warm air, and sometimes warm the air even more, worsening thermal inversion. Santiago suffers from thermal inversion in winter, and the high indexes of pollution are due to the lack of ventilation produced by the thermal inversion.

Rainfall can reverse thermal inversion, improving ventilation and reducing pollution. When drops of water cross the different layers of air, temperature across the warm and cool layers of air is equalized, reversing thermal inversion. Dallarosa et al (2004) also find evidence supporting this claim: "...the low pressure associated with a strong thermal inversion, weak winds and lack of rainfall during the previous 3 days caused atmospheric stagnation and a PAHs peak was achieved." (pg 8)

Summarizing, rainfall first cleans the air, thorough the mechanism described in Rubio et al. (2001) and Ruijgrok and Römer (1993), and furthermore, reverses the thermal inversion, improving the ventilation conditions in the short run[8]

We use deviations from monthly rainfall as our instrument for pollution. We use deviations because we need to control for seasonality as seasons can have an independent effect on birth outcomes (Murray et al, 2000). Hence we include month fixed effects to control for seasonal effects.

For rainfall to get rid of omitted variables bias, we assume that deviations from monthly rainfall during the gestation period are uncorrelated with variables that might appear in ϵ_{ij}. For example, if income is a determinant of birth weight and pollution exposure, we must assume that income is uncorrelated with rainfall shocks. Since the area of study is

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[8] While the evidence for rainfall affecting pollution is quite strong, some authors have written on how pollution itself can *cause* (Cerveny et al, 1998) or *prevent* (Rosenfeld et al, 2000) rainfall. We think this is not an issue with Santiago given its historical monthly pattern of rainfall has not changed in decades. We plot the monthly distribution of rainfall starting in 1910 to 1990 in Figure 4 - assuming pollution was very low in 1910, if pollution causing rain was a concern we should expect drastic changes in the pattern of rainfall over the months. We find this is not the case.

completely urban, we think rainfall shocks are exogenous to things that affect birth weight, except pollution. Using the 2003 CASEN survey, we examined the proportion of people engaged in occupations that might be influenced by rain and we find only 4% of the workforce engaged in such occupations[9].

For rainfall to tackle the problem of measurement error, we assume that rainfall lowers pollution to a point where the heterogeneity in air quality within a municipality becomes absent. A simple example can illustrate this point.

Suppose within a municipality the more educated invest in air filters and breathe cleaner air in general (say of quality 40 PM10), while the uneducated with no air filters breathe worse air (say of air quality 80 PM10). If rainfall reduces pollution and causes air to be of quality 35 PM10, then it does not matter that the more educated have air filters. Hence, the underlying assumption is that rainfall *equalizes* the air quality across income or education groups[10]. Moreover, this equalization is done randomly, since rainfall shocks are assumed orthogonal to personal characteristics and preferences. The key here is that people take pollution reducing measures as a long term measure. If people change behavior due to rainfall shocks (i.e. if the more educated removed air filters after a rainy period) then the instrument becomes invalid.

5. RESULTS

Figure 1 and 2 show the most basic relationship between birth outcomes at month of birth and pollution. It is clear from these figures that there exists an association at least between birth weight (and length) and pollution.

Even though OLS is problematic for various reasons as discussed above, we first show our results using this approach. Second, we control for residential sorting by adopting a fixed effects model. However, as we saw earlier even controlling for residential sorting does not solve the issue of measurement error and heterogeneity within a municipality. The final results use an IV specification using rainfall as an instrument for pollution exposure.

Moreover, we focus on time near the last trimester before birth. The medical literature as well as the epidemiological literature tends to focus on the last trimester as its the most important time in a baby's fetal development. Given our methodology, we can examine this the relationship between timing of pollution exposure and birth weight at the weekly level leading up to birth. Hence we examine the effects of pollution starting at 16 weeks prior to birth.

5.1. **Ordinary Least Squares.** The specification used here is simply:

$$Y_{ij} = \sum_{t=1}^{16} \beta_t P_{tj} + +\gamma \mathbf{X_{ij}} + \epsilon_{ij} \tag{16}$$

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[9] We used occupations like construction, agriculture, street business (street vendors) et cetera.

[10] More generally, we need that rainfall equalizes air quality across groups that matter for birth weight

Where Y_{ij} is the birth outcome of baby i in municipality j, P_{jt} is the average pollution in municipality j in the week t before birth. $\mathbf{X_{ij}}$ are controls for year and month of birth, mother's age and sex of the baby.

Conventional estimates of the effects of pollution on birthweight include as many observable controls as one can find. Using such a methodology, we find insignificant results regarding the effects of pollution on birthweight (Table 1).

The OLS results in Table 2 do not include endogenous controls and seem to suggest that pollution in the last trimester leads to adverse birth outcomes (except for height). Pollution in the last trimester leads to lower birth weight, higher probability of very low birth weight, higher birth length and smaller gestational age. Greater birth length should not necessarily be interpreted as a sign of good health - if we were to think of the overall health of a baby in terms of BMI or Rohrer's Index[11], then lower birth weight and higher birth length implies an even lower measure of overall health. The direction of most of these results seem consistent with previous epidemiological studies.

5.2. **Fixed Effects Model of Residential Sorting.** If we believe that the people who sort into a less polluted neighborhood, have other characteristics that make them have healthier babies, then OLS will overstate the role of pollution. To deal with the issue of residential sorting based on pollution preferences, we introduce a neighborhood fixed effect. Santiago is divided into 34 municipalities and we know in the data the municipality of residence of the mother. We control for not only time invariant characteristics of the municipality, but also growth of the municipality by using the interaction of municipality and year fixed effects. Our regression specification now looks like:

$$Y_{ij} = \sum_{t=1}^{16} \beta_t P_{tj} + \gamma \mathbf{X_{ij}} + \rho_j \mathbf{M_j} + \tau_{jt} \mathbf{M_j} * \mathbf{Y_t} + \epsilon_{ij} \tag{17}$$

Where Y_{ij} is the birth outcome of baby i in municipality j, P_{jt}'s are the average pollution in municipality j in week t before birth. $\mathbf{X_{ij}}$ are controls for year and month of birth, mother's age and sex of the baby. M_j is a dummy for each municipality of residence of the mother, and $M_j * Y_t$ is the interaction of municipality and year fixed effects.

Dealing with residential sorting by introducing municipality fixed effects (Table 3) preserves the general direction of results as found in the OLS specification for most birth outcomes. Moreover, due to the measurement error problem we cannot a priori say whether OLS and even the fixed effects model is an upper or lower bound. We deem the results we have so far as inconclusive at best, and resort to an instrumental variable strategy to pin down the causal relationship between pollution and birth outcomes.

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[11] BMI is $weight/height^2$, while the Rohrer Index is $weight/height^3$

5.3. **Instrument Variables Strategy.** As discussed earlier, our instrument variable strategy is to use rainfall as an instrument for pollution levels over the gestational period. The specification we estimate is:

$$Y_{ij} = \sum_{t=1}^{16} \beta_t P_{tj} + \gamma \mathbf{X_{ij}} + \rho_j \mathbf{M_j} + \tau_{jt} \mathbf{M_j} * \mathbf{Y_t} + \epsilon_{ij} \tag{18}$$

Where P_{jt}'s are instrumented by average rainfall in the respective weeks. Recall that X_{ij} includes year and month fixed effects. Hence, in essence the instrument is utilizing deviations from average monthly rainfall levels.

As we can see in Table 4, the first stage is strong. Higher rainfall is associated with lower levels of pollution. The relationship is made clear in Figure 3. The figure shows the daily variation in pollution in the month of June (a month of high pollution) and the effect that rainfall has on pollution. The dots indicate rainfall days and the higher the dot the more the amount of rainfall. Note that the big drop in pollution occurs when it rains the most.

The second stage results are presented in Table 5. The IV estimates for last 16 weeks of pollution effects are much larger than the OLS and Fixed Effects specifications. A 1 unit increase in average pollution (PM10) in the last 16 weeks decreases birth weight by 7.4 grams. This is a substantial effect. Bell et al's (2007) study in the US found an impact that was 5 times smaller than ours. Other birth outcomes also show significant impacts - birth length reduces, as does gestational age and the probability of being a term birth. In fact, for a 1 std deviation increase in average pollution (around 17 PM10) in the last trimester, gestational age reduces by almost half a week. The probabilities of being LBW and VLBW are also much higher in the IV estimates. Carefully controlling for unobservables as well as measurement error, we conclude that the IV estimates show a large effect of pollution exposure on birthweight.

6. CONCLUSION

This paper finds a causal link between air pollution and birth outcomes. Unlike previous studies that primarily relied on ordinary least squares and fixed effects models, we exploit a unique feature of Santiago's geography and weather to use an instrument variable technique.

We find substantial effects of pollution on birth outcomes. We find that a one standard deviation increase (17 units) in average pollution in the last trimester can decrease birth weight by 125 grams. We find similar negative effects on birth length and gestational age. Moreover the probability of being Low Birthweight increases by 2%.

Given the importance of birth weight for future outcomes in studies such as Black et al (2007), we think there is a high "cost" of pollution in Santiago, that is borne by babies with lower birth weight. For example, Black et al (2007) find that full time income increases by 1% and IQ increases by 0.05 stanine when birth weight increases by approximately 250 grams. While their study is based in Norway, it is likely that the effects of birth weight are larger for developing countries. Taking Black et al's effect on income as the baseline, we compute the present discounted lifetime value of increasing birth weight by 125 grams in Santiago to be around $900 per person[12]. According to our calculations, a 150gm effect can be achieved by reducing average pollution by 17 PM10. The number of children born each year is approximately 80,000. Hence the total gain to the Chilean economy of reducing average pollution by 17 PM10 is around 72 million dollars per year (approximately 0.04% of the Chilean economy). It is important to mention that these are gains if we consider birth weight increase as the *only* benefit of reducing pollution. Elderly mortality, productivity losses due to respiratory illnesses are just a few potential areas of gain by reducing pollution.

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[12] Interest rate used was 5%, which is the current interest rate, and the time horizon used is 40 years. Per capita income of $10,000 was used.

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TABLE 0

SUMMARY STATISTICS

	Mean	Std Deviation
Birthweight (in 100 gms)	33.33	5.47
Pollution (PM10) in last trimester	75.93	17.59
Rainfall (inches) in last trimester	1.023	1.27
Very low birthweight	0.0095	0.1
Low birthweight	0.057	0.23
Height (cms) at birth	49.44	2.67
Gestational age (weeks)	38.64	1.83
Fullterm births	0.92	0.26
Mother's age	27.49	6.72
Female	0.48	

TABLE 1

OLS: BIRTH OUTCOMES AND POLLUTION - COMMON CONTROLS

	Weight (in 100 grams)	Low Birthweight (w<2500 gms)	Very Low Birthweight (w<1500 gms)	Height (cms)
	(1)	(2)	(3)	(4)
Total effect 1-16 weeks before birth	**-0.0014**	**0**	**0**	**0.0038**
	(0.002)	**(0.00006)**	**(0.00002)**	**(0.0028)**
Total effect 1-8 weeks before birth	**-0.0009**	**0.00003**	**0.00001**	**0.0028**
	(0.0016)	**(0.00004)**	**(0.00001)**	**(0.0016)***
Weekly pollution effects				
1 Week before birth	-0.0011	0	0	0.0003
	[0.0005]*	[0.0000]	[0.0000]	[0.0003]
2 Weeks before birth	-0.0007	0	0	0.0001
	[0.0005]	[0.0000]	[0.0000]	[0.0003]
3 Weeks before birth	0.0004	0	0	0.0004
	[0.0005]	[0.0000]	[0.0000]	[0.0003]
4 Weeks before birth	-0.0001	0	0	0.0005
	[0.0004]	[0.0000]	[0.0000]	[0.0004]
5 Weeks before birth	-0.0001	0	0	0.0006
	[0.0006]	[0.0000]	[0.0000]	[0.0003]*
6 Weeks before birth	0.0015	0	0	0.0009
	[0.0005]***	[0.0000]	[0.0000]***	[0.0003]**
7 Weeks before birth	-0.0009	0	0	-0.0002
	[0.0005]*	[0.0000]	[0.0000]**	[0.0003]
8 Weeks before birth	0.0001	0	0	0.0003
	[0.0005]	[0.0000]	[0.0000]	[0.0003]
9 Weeks before birth	0.0001	0	0	0.0005
	[0.0006]	[0.0000]	[0.0000]	[0.0004]
10 Weeks before birth	0	0	0	0.0004
	[0.0006]	[0.0000]	[0.0000]	[0.0004]
11 Weeks before birth	0.0003	0	0	0.0005
	[0.0005]	[0.0000]	[0.0000]	[0.0003]*
12 Weeks before birth	-0.0008	0	0	-0.0003
	[0.0005]	[0.0000]	[0.0000]	[0.0003]
13 Weeks before birth	0.0004	0	0	0.0002
	[0.0005]	[0.0000]*	[0.0000]	[0.0002]
14 Weeks before birth	-0.0016	0	0	-0.0005
	[0.0006]**	[0.0000]	[0.0000]	[0.0003]*
15 Weeks before birth	0.0005	0	0	0.0001
	[0.0005]	[0.0000]	[0.0000]***	[0.0003]
16 Weeks before birth	0.0006	0	0	0
	[0.0006]	[0.0000]	[0.0000]	[0.0002]
Constant	6.6661	0.9918	1.0018	20.1314
	[0.2281]***	[0.0064]***	[0.0025]***	[0.2004]***
Observations	191896	191896	191896	191896

Standard errors in brackets, clustered at municipality level. We have 30 clusters.
* significant at 10%; ** significant at 5%; *** significant at 1%

Notes: Population is all births in Santiago between 2002-2004 (inclusive). Other controls included are dummies for Female, Year, Mother's age and Month of birth. The regressions also control for Mother's education, Mother's occupation, gestational age, birth order, type of birth and day of the week. PM 10 stands for particulate matters with diameter of 10 micrometers or less.

TABLE 2

OLS: BIRTH OUTCOMES AND POLLUTION

	Weight (in 100 grams)	Low Birthweight (w<2500 gms)	Very Low Birthweight (w<1500 gms)	Height (cms)	Gestational Age (weeks)	Fullterm Birth (37-42 weeks)
	(1)	(2)	(3)	(4)	(5)	(6)
Total effect 1-16 weeks before birth	**-0.0027**	**0.0001**	**0.0001**	**0.0022**	**-0.0017**	**-0.00004**
	(0.0038)	**(0.0001)**	**(0.00003)*****	**(0.0029)**	**(0.0012)**	**(0.0001)**
Total effect 1-8 weeks before birth	**-0.0029**	**0.0001**	**0.0001**	**0.0014**	**-0.0013**	**-0.00005**
	(0.0021)	**(0.0001)**	**(0.00002)*****	**(0.0016)**	**(0.0007)***	**(0.00008)**
Weekly pollution effects						
1 Week before birth	-0.0019	0.0001	0	-0.0001	-0.0004	-0.0001
	[0.0006]***	[0.0000]***	[0.0000]*	[0.0003]	[0.0003]	[0.0000]
2 Weeks before birth	-0.0007	0	0	0.0001	-0.0002	0.0001
	[0.0008]	[0.0000]	[0.0000]	[0.0004]	[0.0002]	[0.0000]*
3 Weeks before birth	0.0005	0	0	0.0004	0	0
	[0.0007]	[0.0000]	[0.0000]	[0.0003]	[0.0002]	[0.0000]
4 Weeks before birth	0	0	0	0.0004	-0.0001	0
	[0.0005]	[0.0000]	[0.0000]	[0.0004]	[0.0003]	[0.0000]
5 Weeks before birth	-0.0001	0	0	0.0005	0	0
	[0.0008]	[0.0000]	[0.0000]	[0.0004]	[0.0003]	[0.0000]
6 Weeks before birth	0.0013	0	0	0.0007	0	0
	[0.0007]*	[0.0000]	[0.0000]	[0.0004]*	[0.0003]	[0.0000]
7 Weeks before birth	-0.0013	0	0	-0.0004	-0.0002	0
	[0.0009]	[0.0000]	[0.0000]	[0.0004]	[0.0003]	[0.0000]
8 Weeks before birth	-0.0008	0.0001	0	-0.0002	-0.0005	-0.0001
	[0.0009]	[0.0000]	[0.0000]	[0.0005]	[0.0003]	[0.0000]
9 Weeks before birth	0.0004	0	0	0.0006	-0.0001	0
	[0.0009]	[0.0000]	[0.0000]	[0.0005]	[0.0003]	[0.0000]
10 Weeks before birth	0.0001	0	0	0.0004	-0.0001	0
	[0.0009]	[0.0000]	[0.0000]	[0.0006]	[0.0004]	[0.0000]
11 Weeks before birth	0.0003	0	0	0.0006	0	0
	[0.0006]	[0.0000]	[0.0000]	[0.0003]*	[0.0002]	[0.0000]
12 Weeks before birth	-0.0004	0	0	-0.0002	0.0001	0
	[0.0006]	[0.0000]	[0.0000]	[0.0003]	[0.0002]	[0.0000]
13 Weeks before birth	-0.0004	0	0	-0.0004	-0.0004	-0.0001
	[0.0006]	[0.0000]	[0.0000]***	[0.0003]	[0.0001]***	[0.0000]
14 Weeks before birth	-0.002	0.0001	0	-0.0008	-0.0003	0
	[0.0009]**	[0.0000]*	[0.0000]	[0.0004]*	[0.0002]	[0.0000]
15 Weeks before birth	0.0013	-0.0001	0	0.0004	0.0003	0
	[0.0007]*	[0.0000]	[0.0000]*	[0.0003]	[0.0002]	[0.0000]
16 Weeks before birth	0.0008	0	0	0.0001	0.0001	0
	[0.0007]	[0.0000]	[0.0000]	[0.0003]	[0.0002]	[0.0000]
Constant	34.7447	0.0004	-0.0041	50.577	40.0033	0.9795
	[0.2398]***	[0.0055]	[0.0019]**	[0.1588]***	[0.0740]***	[0.0072]***
Observations	191896	191896	191896	191896	191896	191896

Standard errors in brackets, clustered at municipality level. We have 30 clusters.

* significant at 10%; ** significant at 5%; *** significant at 1%

Notes: Population is all births in Santiago between 2002-2004 (inclusive). Other controls included are dummies for Female, Year, Mother's age and Month of birth and day of the week. Low birthweight is defined as lower than 2500 grams at birth. Fullterm is defined as between 37 and 42 weeks of gestational age. Gestational age is measured in weeks, Height in cms and Weight in 100's of grams. Instruments used are average rainfall in the 3rd trimester and average rainfall in the second trimester. 3rd Trimester is defined as 90 days prior to birth and 2nd Trimester defined as between 90 and 180 days prior to birth. PM 10 stands for particulate matters with diameter of 10 micrometers or less.

TABLE 3

AREA OF RESIDENCE FIXED EFFECTS MODEL - BIRTH OUTCOMES AND POLLUTION

	Weight (in 100 grams)	Low Birthweight (w<2500 gms)	Very Low Birthweight (w<1500 gms)	Height (cms)	Gestational Age (weeks)	Fullterm Birth (37-42 weeks)
	(1)	(2)	(3)	(4)	(5)	(6)
Total effect 1-16 weeks before birth	**-0.0033**	**0.0001**	**0.0008**	**-0.0016**	**-0.0005**	**0.0001**
	(0.0028)	**(0.0001)**	**(0.00005)**	**(0.0014)**	**(0.0011)**	**(0.0001)**
Total effect 1-8 weeks before birth	**-0.0029**	**0.00014**	**0.00006**	**-0.0007**	**-0.0004**	**0.00002**
	(0.0016)*	**(0.00006)****	**(0.00003)****	**(0.0008)**	**(0.0005)**	**(0.00008)**
Weekly pollution effects						
1 Week before birth	-0.0018	0.0001	0	-0.0004	-0.0002	0
	[0.0006]***	[0.0000]**	[0.0000]	[0.0003]	[0.0002]	[0.0000]
2 Weeks before birth	-0.0007	0	0	-0.0001	-0.0001	0.0001
	[0.0007]	[0.0000]	[0.0000]	[0.0004]	[0.0003]	[0.0000]*
3 Weeks before birth	0.0005	0	0	0.0002	0.0001	0
	[0.0007]	[0.0000]	[0.0000]	[0.0003]	[0.0002]	[0.0000]
4 Weeks before birth	-0.0002	0	0	0.0001	0	0
	[0.0006]	[0.0000]	[0.0000]	[0.0003]	[0.0003]	[0.0000]
5 Weeks before birth	-0.0001	0	0	0.0002	0.0001	0
	[0.0007]	[0.0000]	[0.0000]	[0.0003]	[0.0003]	[0.0000]
6 Weeks before birth	0.0013	0	0	0.0004	0.0001	0
	[0.0007]	[0.0000]	[0.0000]	[0.0004]	[0.0003]	[0.0000]
7 Weeks before birth	-0.0011	0	0	-0.0006	-0.0001	0
	[0.0008]	[0.0000]	[0.0000]	[0.0004]	[0.0003]	[0.0000]
8 Weeks before birth	-0.0008	0.0001	0	-0.0004	-0.0004	-0.0001
	[0.0009]	[0.0000]	[0.0000]	[0.0005]	[0.0003]	[0.0000]
9 Weeks before birth	0.0004	0	0	0.0004	0	0
	[0.0008]	[0.0000]	[0.0000]	[0.0004]	[0.0003]	[0.0000]
10 Weeks before birth	0.0002	0	0	0.0001	0.0001	0
	[0.0009]	[0.0000]	[0.0000]	[0.0005]	[0.0004]	[0.0000]
11 Weeks before birth	0.0003	0	0	0.0003	0.0001	0
	[0.0005]	[0.0000]	[0.0000]	[0.0003]	[0.0002]	[0.0000]
12 Weeks before birth	-0.0004	0	0	-0.0003	0.0002	0
	[0.0006]	[0.0000]	[0.0000]	[0.0003]	[0.0002]	[0.0000]
13 Weeks before birth	-0.0004	0	0	-0.0006	-0.0004	0
	[0.0006]	[0.0000]	[0.0000]***	[0.0003]*	[0.0001]**	[0.0000]
14 Weeks before birth	-0.0022	0.0001	0	-0.0011	-0.0003	0
	[0.0009]**	[0.0000]*	[0.0000]	[0.0004]**	[0.0003]	[0.0000]
15 Weeks before birth	0.0012	0	0	0.0003	0.0003	0
	[0.0007]	[0.0000]	[0.0000]	[0.0004]	[0.0002]	[0.0000]
16 Weeks before birth	0.0007	0	0	0	0.0001	0
	[0.0007]	[0.0000]	[0.0000]	[0.0003]	[0.0002]	[0.0000]
Constant	34.3357	0.0015	-0.0063	50.5706	40.0049	0.9769
	[0.1666]***	[0.0068]	[0.0027]**	[0.0824]***	[0.0611]***	[0.0091]***
Observations	191896	191896	191896	191896	191896	191896

Standard errors in brackets, clustered at municipality level. We have 30 clusters.

* significant at 10%; ** significant at 5%; *** significant at 1%

Notes: Population is all births in Santiago between 2002-2004 (inclusive). Other controls included are dummies for Female, Year, Municipality of residence, Mother's age and Month of birth and day of the week. Low birthweight is defined as lower than 2500 grams at birth. Fullterm is defined as between 37 and 42 weeks of gestational age. Gestational age is measured in weeks, Height in cms and Weight in 100's of grams. PM 10 stands for particulate matter with diameter of 10 micrometers or less.

TABLE 4

FIRST STAGE REGRESSIONS

Regression coefficients of the effect of rain on pollution by week

1	2	3	4	5	6	7	8
-2.2667	-2.2406	-2.7116	-2.2646	-2.1169	-2.2667	-2.3632	-2.1209
[0.0481]***	[0.0411]***	[0.0452]***	[0.0353]***	[0.0432]***	[0.0402]***	[0.0424]***	[0.0263]***

9	10	11	12	13	14	15	16
-2.0615	-2.1712	-2.3322	-2.6097	-2.1683	-2.2325	-2.4022	-2.5019
[0.0398]***	[0.0305]***	[0.0371]***	[0.0421]***	[0.0347]***	[0.0334]***	[0.0468]***	[0.0523]***

Notes: All variables in outcome equations are included in the first stage. The general form of the regression is: Pollution in Week X = Rain in week 1 + … + Rain in week X+… + Rain in week 16, where 1<X<16. Only coefficient of rain in Week X is reported in this table.

TABLE 5

IV ESTIMATES - BIRTH OUTCOMES AND POLLUTION

	Weight (in 100 grams)	Low Birthweight (w<2500 gms)	Very Low Birthweight (w<1500 gms)	Height (cms)	Gestational Age (weeks)	Fullterm Birth (37-42 weeks)
	(1)	(2)	(3)	(4)	(5)	(6)
Total effect 1-16 weeks before birth	**-0.074**	**0.0013**	**0.0008**	**-0.038**	**-0.025**	**-0.0018**
	(0.0221)***	**(0.0009)**	**(0.0003)****	**(0.011)*****	**(0.0064)*****	**(0.0008)****
Total effect 1-8 weeks before birth	**-0.035**	**0.0007**	**0.0003**	**-0.0165**	**-0.012**	**-0.0008**
	(0.0104)***	**(0.0004)***	**(0.0001)****	**(0.0052)*****	**(0.0030)*****	**(0.0004)***
*Weekly pollution effects**						
1 Week before birth	-0.0047	0.0002	0.0001	-0.0013	-0.0017	-0.0002
	[0.0019]**	[0.0001]**	[0.0000]*	[0.0011]	[0.0006]***	[0.0001]**
2 Weeks before birth	-0.001	0.0001	-0.0001	-0.0002	0.0002	0.0001
	[0.0022]	[0.0001]	[0.0000]*	[0.0012]	[0.0007]	[0.0001]
3 Weeks before birth	-0.0046	0.0001	0.0001	-0.0024	-0.0019	-0.0002
	[0.0024]*	[0.0001]	[0.0000]**	[0.0012]*	[0.0007]**	[0.0001]**
4 Weeks before birth	-0.0034	0	0	-0.0018	-0.0013	0
	[0.0025]	[0.0001]	[0.0000]	[0.0013]	[0.0010]	[0.0001]
5 Weeks before birth	-0.0105	0.0002	0.0002	-0.0042	-0.0033	-0.0003
	[0.0040]**	[0.0002]	[0.0001]*	[0.0021]*	[0.0011]***	[0.0002]
6 Weeks before birth	0.0004	-0.0001	0	-0.0013	-0.0005	0
	[0.0032]	[0.0001]	[0.0000]	[0.0015]	[0.0010]	[0.0001]
7 Weeks before birth	-0.0068	0.0001	0.0001	-0.0026	-0.0024	-0.0001
	[0.0040]*	[0.0002]	[0.0001]	[0.0022]	[0.0012]*	[0.0002]
8 Weeks before birth	-0.0047	0.0001	-0.0001	-0.0027	-0.001	-0.0001
	[0.0032]	[0.0001]	[0.0001]	[0.0017]	[0.0011]	[0.0001]
9 Weeks before birth	-0.0071	0.0003	0.0002	-0.0033	-0.0032	-0.0003
	[0.0049]	[0.0002]	[0.0001]**	[0.0026]	[0.0014]**	[0.0002]*
10 Weeks before birth	-0.0057	-0.0001	-0.0001	-0.0033	-0.0016	-0.0001
	[0.0034]*	[0.0002]	[0.0001]	[0.0018]*	[0.0014]	[0.0002]
11 Weeks before birth	-0.0061	0.0002	0.0001	-0.0024	-0.0024	-0.0003
	[0.0039]	[0.0002]	[0.0001]	[0.0020]	[0.0012]*	[0.0002]
12 Weeks before birth	-0.0028	-0.0001	0	-0.0021	-0.0009	0
	[0.0029]	[0.0002]	[0.0001]	[0.0014]	[0.0010]	[0.0001]
13 Weeks before birth	-0.0051	0.0002	0.0001	-0.0022	-0.0021	-0.0001
	[0.0034]	[0.0002]	[0.0001]*	[0.0020]	[0.0011]*	[0.0001]
14 Weeks before birth	-0.006	0.0001	0	-0.004	-0.0011	-0.0001
	[0.0028]**	[0.0001]	[0.0000]	[0.0013]***	[0.0008]	[0.0001]
15 Weeks before birth	-0.005	0.0001	0.0002	-0.0025	-0.002	-0.0001
	[0.0042]	[0.0002]	[0.0001]*	[0.0022]	[0.0013]	[0.0002]
16 Weeks before birth	-0.0011	-0.0001	0	-0.0017	-0.0002	-0.0001
	[0.0022]	[0.0001]	[0.0000]	[0.0011]	[0.0007]	[0.0001]
Constant	37.9327	-0.0671	-0.0498	52.3544	41.2375	1.0781
	[1.2150]***	[0.0592]	[0.0227]**	[0.6426]***	[0.3397]***	[0.0432]***
Observations	191896	191896	191896	191896	191896	191896

Standard errors in brackets, clustered at municipality level. We have 30 clusters.

* significant at 10%; ** significant at 5%; *** significant at 1%

Notes: Population is all births in Santiago between 2002-2004 (inclusive). Other controls included are dummies for Female, Year, Municipality of residence, Mother's age and Month of birth and day of the week. Low birthweight is defined as lower than 2500 grams at birth. Fullterm is defined as between 37 and 42 weeks of gestational age. Gestational age is measured in weeks, Height in cms and Weight in 100's of grams. PM 10 stands for particulate matter with diameter of 10 micrometers or less. *Instrumented by average rainfall in that time period. First stage F-Statistic is around 84.

FIGURE 1

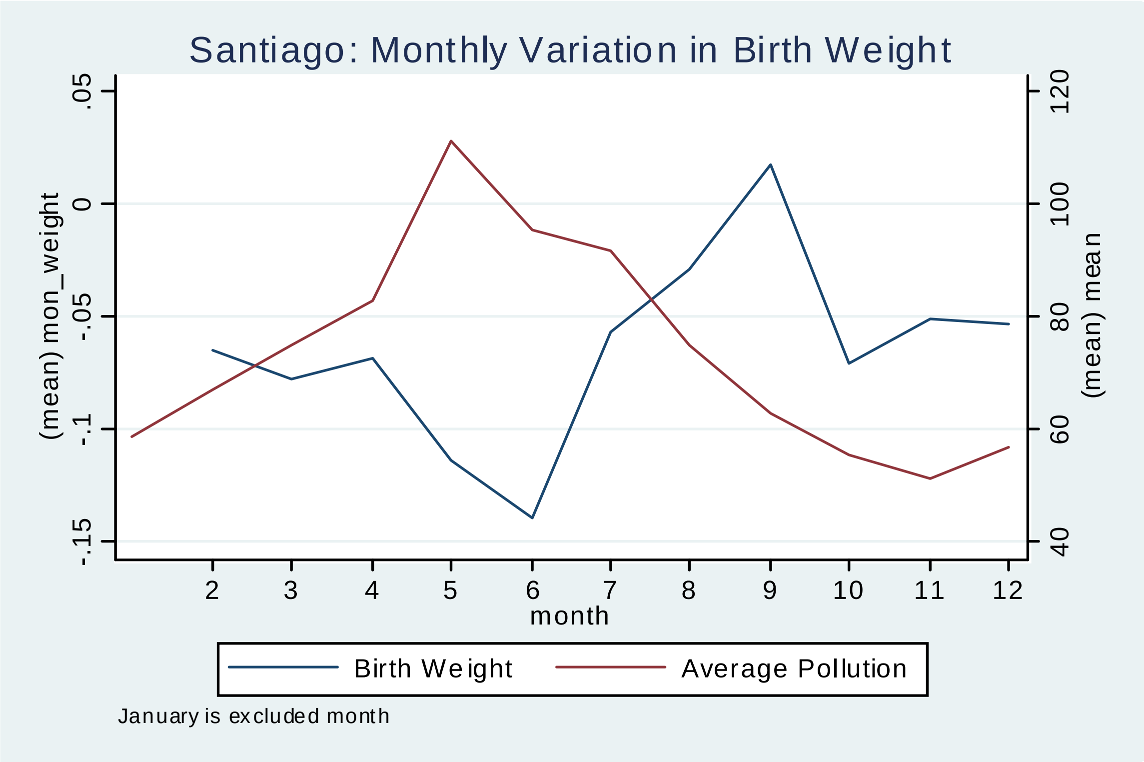


FIGURE 2

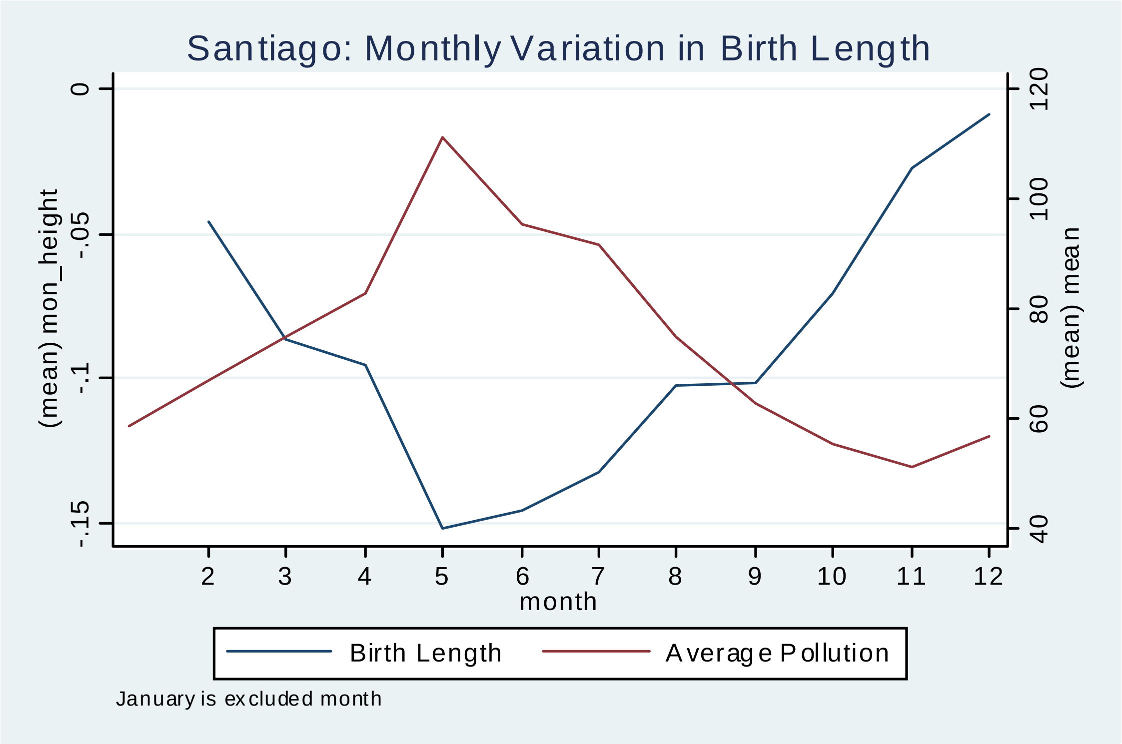


FIGURE 3

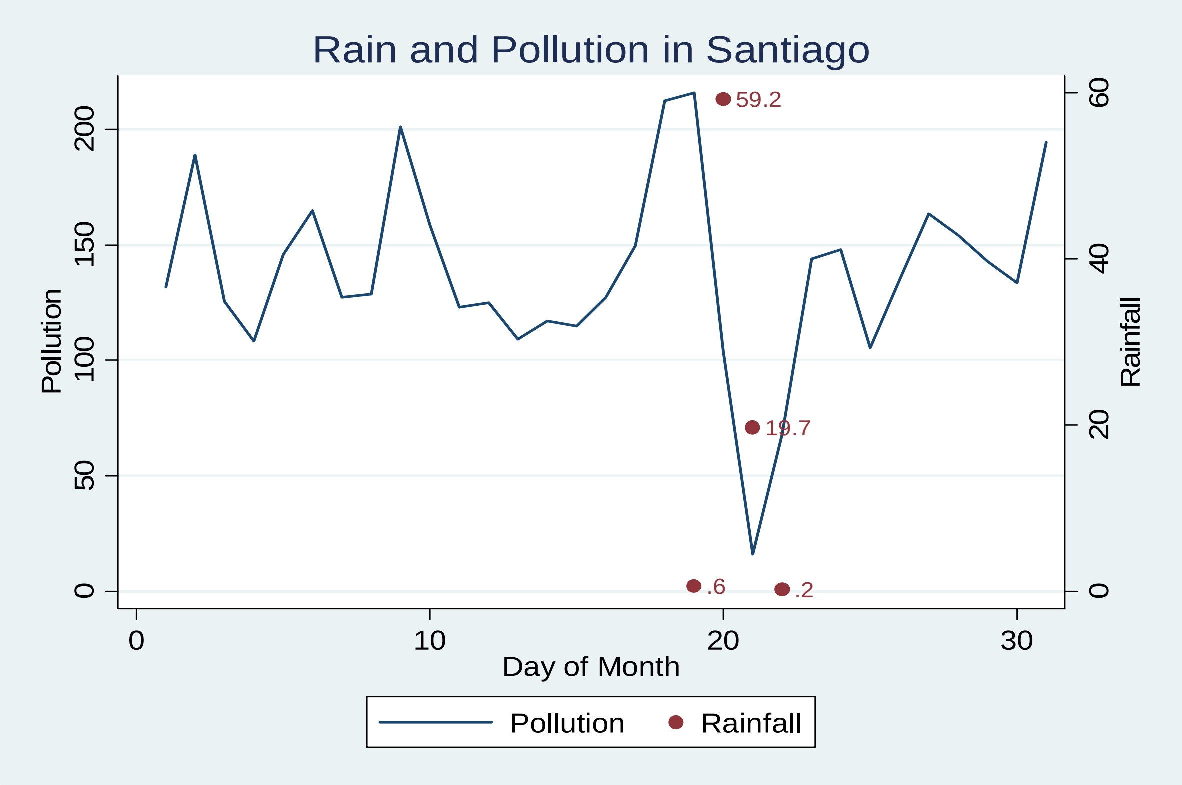
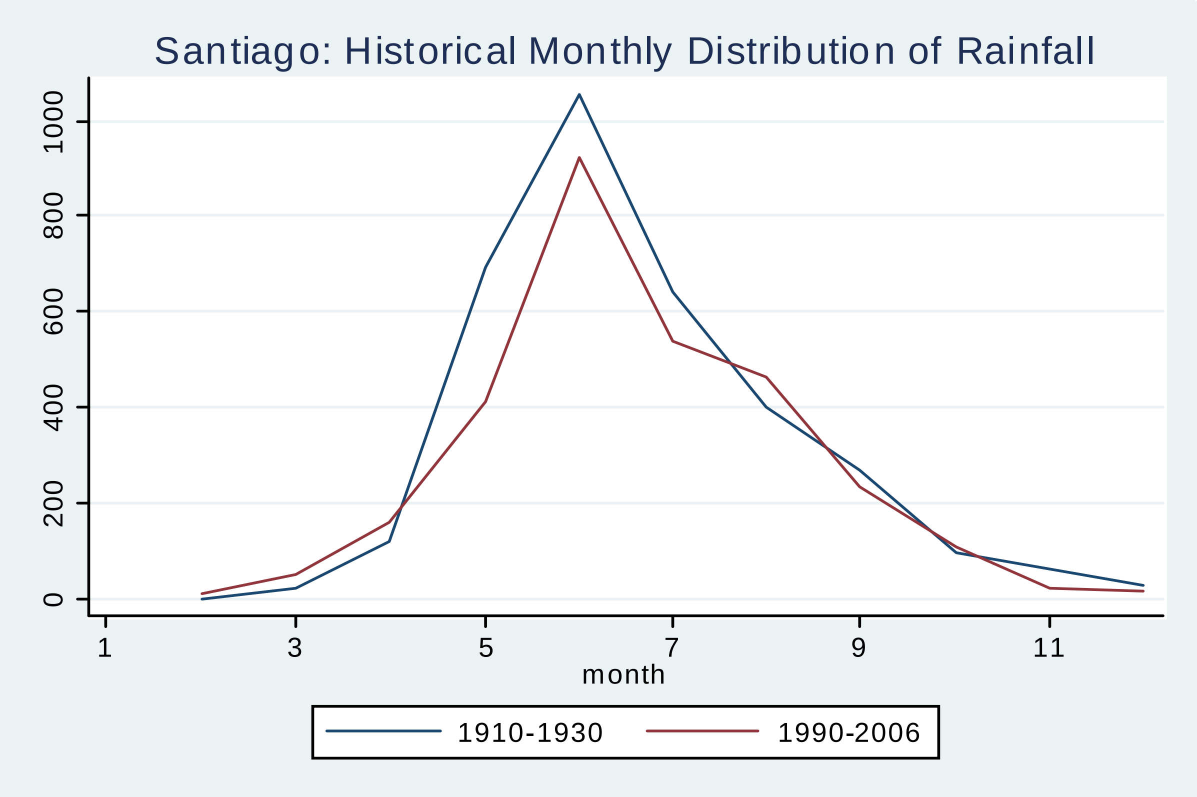
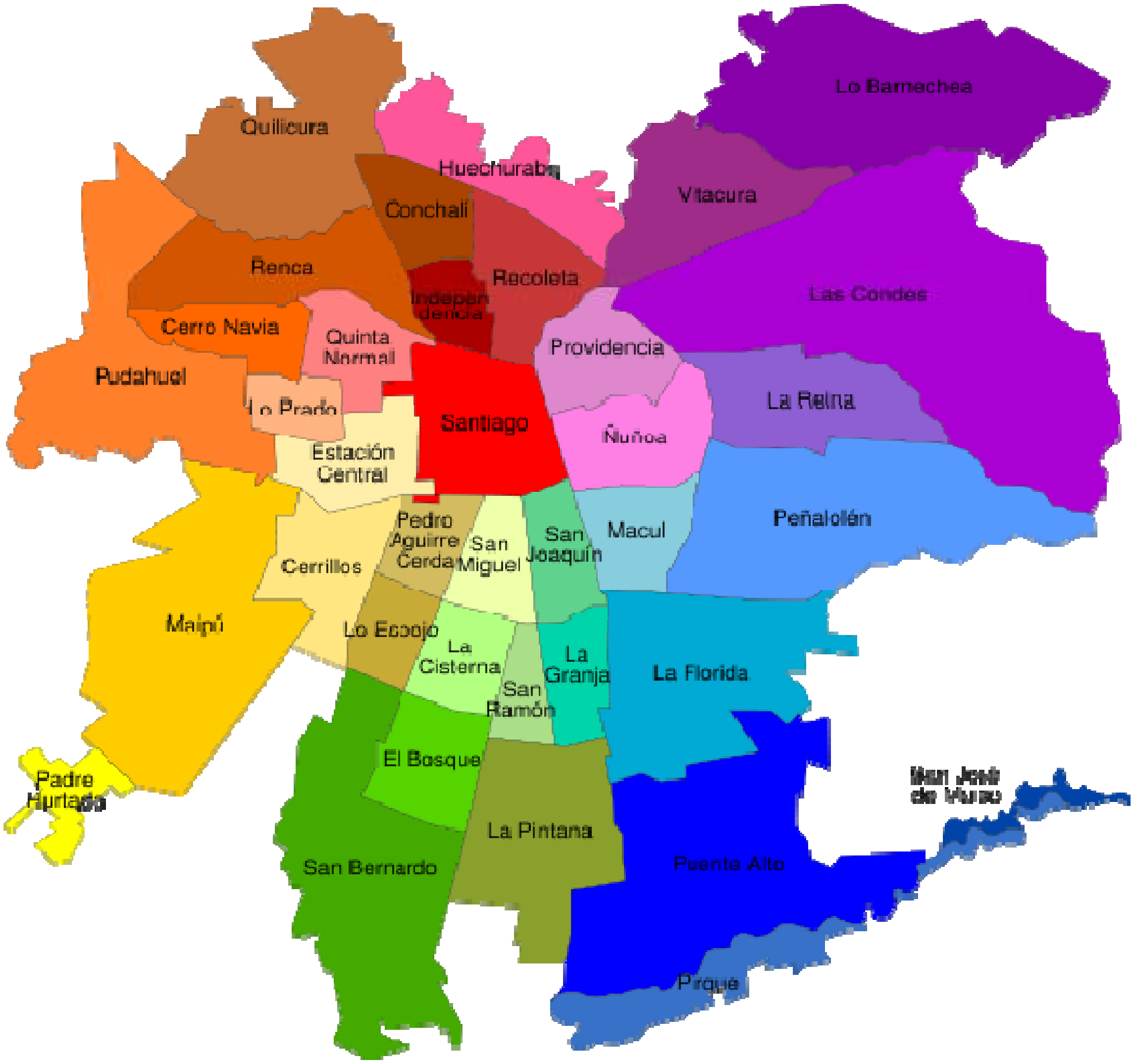


Figure displays the relationship between rainfall and pollution for the month of June in Santiago

FIGURE 4


Santiago: Historical Monthly Distribution of Rainfall
0
200
400
600
800
1000
1
3
5
7
9
11
month
1910-1930
1990-2006

MUNICIPALITY MAP OF SANTIAGO



Santiago on a polluted day in June

Santiago after it rains in June

The HUGE mountain is made invisible by the smog!!