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Abstract*

This study explores the impact of air pollution on adverse birth outcomes. The study focuses on the effect of breathable particulate matter with diameter of 10 micrometers or less (PM10) on the likelihood of premature birth and low birth weight (LBW). The study exploits the fact that in 2011 the ashes and dust resulting from the eruption of the Puyehue volcano in Chile substantially increased exposure to PM10 in Montevideo, Uruguay. Using prenatal and birth data from the Perinatal Information System for 2010-2012, it is found that increases in quarterly averages of PM10 concentrations beyond 50 $\mu g/m^3$ decrease birth weight and increase the likelihood of LBW and prematurity at increasing rates. The results also suggest that the effect of PM10 on birth weight works mainly through a higher likelihood of prematurity, rather than through intrauterine growth retardation. The effects increase with each trimester of pregnancy: exposure during the third trimester is the most dangerous.

JEL classifications: Q53, I12

Keywords: Particulate matter, Pollution, Low birth weight, Pre-term birth

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1. Introduction

Between June and November of 2011, the southern cone of South America was exposed intermittently to clouds of ashes, sand, and pumice as a result of a series of eruptions in the Puyehue-Cordon Caulle volcanic complex in Chile. The first cloud of dust arrived in Montevideo two days after the June 4 eruption and completed its first round trip around the planet in 18 days. In June and July, daily concentrations of particulate matter of up to 10 micrometers (PM10)[1] in Montevideo exceeded the WHO guideline value of 50 μg/m³ on 60 percent of days and were higher than 100 μg/m³ on 30 percent of days (WHO, 2006). November showed similarly high levels of PM10 concentration. Exploiting this natural phenomenon, we analyze the association between acute and intensive exposures to PM10 and the probability of low birth weight (LBW) and pre-term birth (PTB) for births that took place in Montevideo between 2010 and 2012.

Slama et al. (2008) argue that particulate matter may affect perinatal outcomes through various potential mechanisms. For example, it could influence maternal-placental exchanges and hence fetal growth through changes in plasma viscosity and artery vasoconstriction. PM could also induce inflammatory processes that alter maternal immunity and lead to increased susceptibility to infections. These infections may in turn induce pre-term labor or intrauterine growth retardation (IUGR).

LBW and PTB are commonly used as proxies for infant health and are markers for poor health during the life course (McCormick, 1985; Petrou, Sach and Davidson, 2001; Boardman et al., 2002; Black, Devereux and Salvanes, 2007). In particular, LBW has been associated with higher morbidity and lifetime health costs, as well as early mortality (see Currie, 2009 for a review of this literature). Moreover, several authors stress that LBW serves as an important mechanism for the intergenerational transmission of economic status (Currie and Madrian, 1999; Grossman, 2000; Case, Fertig and Paxson, 2004; Behrman and Rosenzweig, 2005; Currie and Moretti, 2005; Currie, 2009).

[1] Particulate matter is a complex mixture of extremely small particles and liquid droplets made up of acids (nitrates and sulfates), organic chemicals, metals, and soil or dust particles. Particles are classified according to their size, generally measured in micrograms per cubic meter of air (μg/m^3) or micrometers. Because particles below 10 micrometers in diameter generally pass through the respiratory tract, they can affect the heart and lungs, representing a hazard to health. Particles between 2.5 and 10 micrometers in diameter are known as “inhalable coarse particles” and are generally found near roadways and dusty industries. Particles of 2.5 micrometers in diameter or less are referred to as “fine particles” and are likely to be found in smoke and haze. These particles can be directly emitted from sources such as forest fires, or they can form when gases emitted from power plants, industries and automobiles react in the air (EPA, 2014).

A growing number of investigations have analyzed the relationship between ambient air pollutant concentrations and measures of perinatal health, such as LBW and PTB.[2] The results of this literature are mixed and difficult to synthesize (Parker et al., 2011). Stieb et al. (2012) review the magnitude and sign of the associations found in 62 primary studies. The authors provide forest plots of the estimates of the effects of breathable suspended particles (PM10), fine particles (PM2.5), carbon monoxide (CO), nitrogen dioxide (NO2), sulfur dioxide (SO2), and ozone (O3) ambient concentrations on weight at birth and probability of LBW and PTB. While more consistent in the case of PM10, the estimates are disperse and show ambiguous signs.

This lack of robustness could be partly explained by distinct methodological approaches, including differences in the way investigators assess the variation in mothers' exposure to ambient air pollution, as well as differences in the set of confounders considered. For example, some studies capture exposure to pollution on a spatio-temporal basis, analyzing variations across sites and time, while others investigate only variation over time. In terms of confounders, few studies consider local weather conditions, adjustment for season of conception, or if the mother smokes, and many lack controls for gestational age or mother's socioeconomic status (Woodruff et al., 2009). Failing to adjust for relevant explanatory variables can lead to selection biases, particularly because poor people tend to live in areas with higher exposure to ambient pollutants. Furthermore, failure to adjust may stem from longitudinal identification problems, as the effects of pollution could mask other trends. These methodological problems have led some authors to question the causality of prior findings and the degree to which they are consistent (Glinianaia et al., 2004; Maisonet et al., 2004; Woodruff et al., 2009; Stieb et al., 2012.). As a response to the lack of methodological coherence in the literature, Dadvand et al. (2013) used a common protocol to re-estimate the results of previous published articles in 14 centers and nine countries. While the results were more consistent, dispersion was still high.

One potential additional source of discrepancy is the assumption that the effect of PM10 outdoor concentration on perinatal health is linear, without allowing for marginal effects to vary at different levels of exposure. This assumption has been so prevalent that Stieb et al. (2012) expressed the estimates of the original studies assessed in their study in terms of pollutants' increments equal to the mean increase in concentration of the corresponding pollutant in

[2] See Stieb et al. (2012) for the latest review of the literature. Other reviews include Šrám et al. (2005), Currie, Neidell and Schmieder (2009) and Woodruff et al. (2009).

Canadian cities between 1981 and 2006. If effects were non-linear, part of the noted variation in available estimates could be explained by different marginal effects at different levels of the pollutant that mothers are exposed to. In fact, the median concentration of pollutants varies considerably across studies (Stieb et al., 2012; Dadvand et al., 2013).

Most investigations of the association between ambient air concentration of pollutants and birth outcomes focus on developed countries. The 62 studies identified by Stieb et al. (2012) cover 39 locations. Nearly half the studies (27) were conducted in locations in North America, 18 in Europe, four in Australia, 10 in Asia and three in Brazil. Out of the 10 Asian studies, seven are from South Korean cities, two from cities in Taiwan and one from Beijing. The evidence for Latin America is even scarcer, with only three studies conducted around the city of Sao Paulo in Brazil (Gouveia, Bremner and Novaes, 2004; Medeiros and Gouveia 2005; Nascimento and Moreira, 2009). This gap in the literature is quite relevant because the impact of particulate matter on birth outcomes may be stronger in less developed countries, where higher fractions of the population face nutrition and health limitations, and health services are less developed.

Our paper contributes to the literature on outdoor ambient air pollution and perinatal health in several ways. First, by exploiting an acute and intensive increase in ambient pollution in a city with typical low levels of PM10, we isolate the contemporaneous effects of pollution from chronic or cumulative effects. Most previous studies have been conducted in cities permanently exposed to high levels of air pollution. The distinction may be increasingly important in the years to come if natural phenomena affecting air quality become more prevalent.[3] Second, we exploit exogenous variations in pollution resulting from a natural event that affected the whole city, minimizing concerns about cross-sectional selection and temporal biases. To reinforce our identification, we control for several maternal characteristics, including mothers' pre-pregnancy characteristics, use of prenatal care, smoking during pregnancy, pregnancy medical conditions, and seasonality of conception (Currie and Schwandt, 2013). Most important, we adjust for gestational age at birth, seeking to distinguish the effects of PM10 on birth weight that occur through intrauterine fetal growth from those caused by pre-term delivery. Few other studies explore the effects of pollution on PTB or include gestational age at birth as a

[3] There is strong evidence of a correlation between heat waves and an increase in concentrations of PM10 (Katsouyanni and Analitis, 2009). For example, PM10 increased an estimated 30 percent during heat wave days in Athens in the last decade (Papanastasiou, Melas and Kambezidis, 2013). The effect on human health of these non-marginal increases in air pollution concentrations during heat waves appears to be substantial (Fischer, Brunekree and Lebret, 2004; Monteiro et al., 2013).

control when analyzing the association between pollution and birth weight. We also condition on time variant variables such as income per capita, weather, and quadratic time trends. Finally, we focus on the effects of air quality on birth outcomes in a less developed country, adding to the relatively scarce evidence available for these countries.

We find that exposure to high levels of PM10 during the second and third trimester of the pregnancy decreases birth weight and increases LBW. Most of these detrimental effects operate through an increase in the probability of PTB. We also find that increases in exposure during the first trimester are associated with beneficial birth outcomes, an effect we hypothesize could be driven by a higher rate of spontaneous abortions.

2. Data

2.1 Pregnancy and Delivery Data

We analyze births that took place in Montevideo during 2010-2012 and that were registered in the Perinatal Information System (CLAP, 2001). The Perinatal Information System is an electronic registry containing perinatal histories and covering about 98 percent of all pregnancies in the country.

The main outcomes in our analysis are birth weight, the likelihood of low birth weight and the likelihood of a PTB. Birth weight is measured in grams. Low birth weight is a binary variable that takes the value of 1 if the birth weight is 2,500 grams or less, and 0 otherwise. We define a delivery as pre-term if it occurs before the 37^{th} week of gestation. Table 1 shows a rate of LBW of 7.4 percent and a likelihood of prematurity of 8.3 percent in all deliveries that took place in Montevideo during the period of analysis.

We consider several maternal characteristics that contribute to maternal heterogeneity: mother's age, education level (primary school completed, middle school completed, or high school completed), marital status, mother's smoking status, onset of medical care during pregnancy, pregnancy-specific conditions such as pre-eclampsia, eclampsia, and hypertension, and the child's gender. Almost 70 percent of women belong to the 20-34 age-group, 32 percent are high school graduates and 39 percent have not completed middle school. The majority of mothers (54 percent) live under cohabitation arrangements, 27 percent are married, and 18 percent are single. One out of four women reports smoking during the pregnancy. The average onset of prenatal care is during the 12^{th} week of gestation.

Finally, we consider indicators of prenatal care clinics. There are 74 prenatal care clinics in our data: 50 clinics are public, covering the poorest fraction of the population (40 percent of all deliveries), and the rest are private clinics that provide services to the population in the formal labor market or their dependents through national social insurance (National Integrated Health System or SNIS).

We drop multiple births and births that showed birth weights below 300 grams or above 8000 grams. Overall, our data include 60,102 observations. Almost 24,000 of these pregnancies were exposed to high levels of particulate matter in June, July and November of 2011 due to the ashes from the Puyehue eruption.

2.2 Air Quality

The air quality data come from the Environmental Quality Lab of the Municipal Government of Montevideo. This lab is in charge of the city's air quality monitoring network, which has been in operation since 2003. After using manual stations for several years, in 2009 the network incorporated the first automatic station in the area of Colón, North of Montevideo.[4] This was the only automatic monitoring station in Montevideo operating throughout the full period of analysis (2009-2013), measuring air quality (PM10, SO2, CO, and, NO2) on a daily basis. Our variable of interest is ambient air 24-hour concentration of PM10, which is strongly associated with the Puyehue-Cordon Caulle complex eruptions (see Table 6).

Exposure to PM10 during a pregnancy is computed by averaging out measures of 24-hour PM10 concentration for each trimester. We calculate the date of initiation of the pregnancy by subtracting the gestational age at birth, as assessed by the obstetrician at delivery, from the date of birth.[5] For each pregnancy, we match each week of the pregnancy with the corresponding average PM10 for that week, and then compute the average exposure to PM10 in the first, second, and third trimester. Exposure to PM10 during the third trimester depends on the term of gestation. For full-term births (91 percent of our sample), PM10 during the third trimester is the average PM10 air concentration in the last three months of the pregnancy. For pre-term births, exposure during the third trimester is computed as the average in air quality from gestational

[4] In April 2012 the system incorporated a new automatic station, and two more in 2014. We do not use this information because we only have births up to December 2012.
[5] The obstetrician estimates the newborn's gestational age on the basis of the mother's last menstrual period, past ultrasounds, and a clinical assessment of the newborn.

week 28 to delivery. Seven percent of all births occur between the 32^{nd} and 36^{th} weeks of gestation (have at least two months of exposure in the third trimester) and only 1 percent happen between gestational weeks 28 and 31 (only one month of exposure).

While three other manual stations in the city produced data on PM10 between 2009 and 2013, we chose to work with the automatic station because of its higher precision. Samples in the manual stations are obtained every six days and are more likely to miss extreme episodes. In addition, we are exploiting an exogenous variation in pollution resulting from a single natural phenomenon that affected the whole country. This variation is several times higher than the intra-neighborhood variation in air quality in Montevideo, which is also fairly low in absolute terms. This can be seen in Table 2, which depicts PM10 temporal and spatial variation from three manual monitoring stations located in different spots of the city. When PM10 is averaged at the trimester level, temporal variation (i.e., within stations) is almost three times the geographic variation (i.e. between stations). Restricting the analysis to those observations near the three monitoring stations would impose severe restrictions in terms of sample size (only a small fraction of the data can be geocoded around those stations) and of precision (automatic stations have better measures of PM10 than manual stations). We thus conduct our main analysis on the basis of data from the automatic station and then use measures from the manual stations to check for robustness.

Figure 1 shows monthly averages of PM10 in Montevideo and highlights the dates that the volcanic ashes from the Puyehue arrived in the city. The number of fine particles measured in a 24-hour lapse rose to levels well above 50 during June, July and November 2011. The average level of PM10 in the third trimester[6] was 23.7 $\mu g/m^3$ for pregnancies not exposed to the Puyehue ashes, and 58 $\mu g/m^3$ for pregnancies exposed to the ashes (see Table 1). Table 1 shows also that the fraction of days that PM10 exceeded the threshold of 50 in a non-exposed pregnancy during the 2010-2012 period was 7 percent. The fraction of days of exposure increased fourfold (to 29 percent) when considering pregnancies exposed to the volcano eruption in 2011.

[6] We report only third trimester estimates for the sake of space. Averages for the first and second trimester are in the same ranges.

2.3 Weather and Other Controls

We obtain information about temperature, air pressure, winds, humidity, and precipitations from the National Institute of Meteorology.[7] For each weather variable, we construct trimester-of-pregnancy-specific averages following the same procedure as with PM10. We additionally adjust for income per capita using monthly data for Montevideo from the Uruguayan National Household Survey.

3. Methodology

We estimate the associations between mother's average exposure to PM10 in each trimester and perinatal outcomes controlling for a wide array of covariates. We use Ordinary Least Squares estimation (OLS) as our main approach and check for robustness using logistic models when the dependent variable is dichotomous (probability of LBW and PTB). Our first specification takes the form:

$$Y_{it} = \alpha_0 + \alpha_1 PM10_{t1i} + \alpha_2 PM10_{t2i} + \alpha_3 PM10_{t3i} + X_i'\alpha_4 + Z_{t1}'\alpha_5 + Z_{t2}'\alpha_6 + Z_{t3}'\alpha_7 + \alpha_8 t + \alpha_9 t^2 + \mu_j + \theta_m + \varepsilon_{it} \quad (1)$$

where Y_i is LBW, birth weight, or PTB in pregnancy i gestated at time t; $PM10_{t1i}$ is the average exposure to PM10 during the first trimester for pregnancy i gestated at time t; $PM10_{t2i}$ is the average exposure to PM10 during the second trimester for pregnancy i gestated at time t; and $PM10_{t3i}$ is the same for the third trimester (where the length of the third trimester depends on i's birth date). The vector X_i captures mother's socio-demographic and behavioral characteristics, as well as pregnancy-specific conditions. The vectors Z_{t1}, Z_{t2}, Z_{t3} represent time-varying variables, such as weather and real income per capita, which are common across all pregnancies gestated at time t and are constructed in the same way as pollution. We also adjust for a quadratic time trend to capture underlying trends in perinatal birth outcomes. Finally, the parameters μ_j and θ_m represent, respectively, prenatal care center fixed effects, and month of gestation fixed effects to capture seasonality in month of conception. Currie and Schwandt (2013) find a sharp trough in gestation length among babies conceived in late spring, an effect they attribute to higher influenza prevalence in winter, when these babies are nearing full term.

[7] We obtain daily data for three weather monitoring stations in the East, North, and West of Montevideo (Carrasco, Prado, and Melilla), and average out the indicators across all three stations.

To assess whether the effects of air pollution on perinatal health work through an increase in the likelihood of pre-term delivery or via intrauterine growth retardation, we use two alternative specifications of the LBW and birth weight regressions: one adjusting for gestational age at the time of delivery and the other using no adjustment for this measure. All regressions estimate robust standard errors to account for heteroskedasticity.

A second specification adds a quadratic term for PM10 in each trimester, trying to capture non-linear effects of ambient air pollution.

An interesting question is whether air pollution affects women of poor socio-economic status more than higher income women. Women with poorer health characteristics or habits could be more likely to be affected by levels of particulate matter that exceed the recommended threshold. We explore this question by interacting the PM10 measures with health insurance type (public versus private) and with indicators of high school completion. We also interact PM10 with an indicator of tobacco consumption.

For robustness, we re-estimate the core model using data from the three manual monitoring stations in Montevideo. We use this data in two ways. First, we construct a new measure of PM10 concentration in each trimester as the average PM10 from the three manual stations, and assign each pregnant woman the pollution level that results from this average. Identification in this strategy is again based on temporal variation. In an alternative analysis, we select women attending prenatal care clinics in a radius of 2.5 km of each manual monitoring station. This analysis attempts to match each mother with the air quality in the area where she seeks care. This analysis exploits both temporal and spatial variation in PM10 between monitoring stations, but at the cost of a much lower number of observations and less accurate measures of PM10.

4. Results

4.1 Core Analysis

Table 3 shows the effects of average exposure to PM10 during each trimester of the pregnancy on the outcomes of interest (the probability of LBW, birth weight, and the probability of PTB) using a linear specification for PM10. Apart from the control variables described in Table 1, each regression adjusts for prenatal care center fixed effects, month of gestation and a time trend with a quadratic specification.

Average exposure to PM10 is measured in tens of μg/m³. The first two columns depict the results for LBW and birth weight without controlling for gestational age at birth. We begin by describing the estimates of exposure to PM10 during the second and third trimesters, which have the hypothesized signs. The first column shows that a 10 μg/m³ increase in PM10 during the second trimester of the pregnancy increases the likelihood of LBW by 1 percentage point. The impact of a similar increase in PM10 during the third trimester is 2.2 percentage points (see Column 1). When analyzing birth weight (Column 2), our findings indicate that a 10 μg/m³ increase in PM10 during the second trimester reduces birth weight by 22 grams, and the effect rises to 56 grams when the exposure occurs in the third trimester. Columns 3 and 4 show that the effects of PM10 on LBW decrease in magnitude and lose statistical significance once we control for the number of weeks of gestation at birth. As suggested by the findings in Column 5, the effect of PM10 on the probability of LBW and birth weight is driven primarily by an effect on prematurity. A 10 μg/m³ increase in exposure to PM10 during the second and third trimester is associated with rates of prematurity that are 1.4 and 3 percentage points higher, respectively.

While results for the second and third trimester suggest a distinct negative effect of particulate matter on perinatal health, our estimates for the first trimester appear, at first sight, to be counterintuitive. A 10 μg/m³ increase in PM10 concentration reduces the probability of low birth weight by 1.7 percentage points, increases weight by 42 grams and reduces the likelihood of prematurity by 2 percentage points. One potential explanation is that the coefficients are biased due to failure to adjust for variables, such as economic activity, associated both with PM10 and birth outcomes. We dismiss this explanation on several grounds. First, and as shown below, the large fluctuations in PM10 observed in our data occur during the Puyehue eruption; the levels of PM10 concentration do not shift much with economic activity and are usually within the recommended thresholds in periods beyond the Puyehue eruption. Second, we still control for a measure of real income per capita at the city level, which should capture any remaining association with industrial activity and family income. Third, if an issue of omitted variable bias is involved, it is not clear why we should expect biases in the coefficients for the first trimester and not for the other trimesters.

Another explanation is that higher levels of PM10 in the first trimester increase the risk of spontaneous abortions. Under this hypothesis, an increase in exposure to pollution during the first trimester would be associated with lower rates of prematurity and higher weight at birth because only the healthier babies survive the first trimester. Unfortunately, we cannot directly test this hypothesis due to lack of registries on aborted pregnancies in our data. However, recent literature has identified similar effects. In particular, Enkhmaa et al. (2014) and Moridi, Ziaei and Kazemnejad (2014) find strong statistical correlations between ambient air pollutants and spontaneous abortions in Mongolia and Iran, respectively.

Our second specification models a non-linear association between pollution and perinatal health, adding a set of quadratic terms for the levels of PM10 in each trimester to equation (1). Results are presented in Table 4. The estimated main and quadratic marginal effects of PM10 are statistically significant for every trimester in the LBW, birth weight, and PTB models. For "low" levels of PM10, however, the predominant coefficient of PM10 is negative when explaining the probability of LBW and positive when explaining birth weight. In other words, PM10 begins to have a detrimental impact on weight at birth only above certain threshold levels of particulate matter concentration. As before, we find no significant effects of exposure to PM10 on birth weight when controlling for gestational age (Column 4), but find a significant effect of PM10 exposure in the third trimester on LBW (Column 3), smaller than that in Column (1). Finally, we find strong effects on PTB, suggesting that PM10 levels above a certain threshold mostly affect birth weight through a higher likelihood of prematurity (Column 5).

Another way to see the results in Table 4 is to calculate the non-linear marginal effects for different levels of PM10 in each trimester.[8] We do this in Table 5. For example, Columns (2), (5), and (8) depict the aggregate marginal effect of PM10 concentration on birth weight in the first, second and third trimester, respectively, for levels of PM10 concentrations below 50 μg/m³, 40 μg/m³, or 30 μg/m³, depending on the trimester.

For levels of PM10 below certain thresholds, we observe positive non-linear marginal effects (the poorer the air quality, the higher the birth weight). These thresholds range from 50 μg/m³ in the first trimester to 40 μg/m³ in the second trimester and 30 μg/m³ in the third. Beyond these thresholds, the effects of PM10 concentration on birth weight become harmful (i.e., the higher the trimester average concentrations of PM10, the lower the birth weight). In addition, the effects increase with the trimester: they are higher in the third trimester, as compared to the second, and higher in the second trimester, as compared to the first. As an example, an increase from 90 to 100μg/m³ in the trimester average PM10 concentration decreases birth weight by 67

[8] We report marginal effects only in the ranges of PM10 observed in the data.

grams if it occurs in the first trimester, by 300 grams if it occurs in the second trimester, and by 510 grams if it occurs in the third trimester. These reductions are basically driven by an increase of 0.03, 0.19 and 0.30 percentage points in the probability of a PTB, respectively. Figures 2, 3 and 4 illustrate the marginal effects of PM10 concentration on LBW, birth weight and prematurity for different levels. These figures highlight the increase in marginal effects as the ambient air pollution increases, as well as the relatively more damaging effect of exposure to PM10 during the third trimester.

Our identification strategy relies on the variation of PM10 concentration over time. Thus, the consistency of our estimates depends closely on the degree of exogeneity in the temporal variation of the PM10 measure. We investigate this issue by conducting a linear regression (OLS) of PM10 concentration on several potential drivers: i) the activity level of the industrial sector in the city of Montevideo; ii) the activity level of the state-owned oil refinery, located in the city harbor, as a source of emissions but also as an indicator of the consumption level of liquid fuels; iii) the activity level of the "Batlle" power plant based on carbon, fuel oil, and other fossil fuels (this plant is also located in the city harbor, and is used basically during consumption peaks, or during droughts, to support hydroelectric generation); iv) a dummy equal to one in the months in which the volcano Puyehue erupted, and v) weather variables (rain and wind). The results, displayed in Table 6, show that the eruptions of the Puyehue volcano were the principal drivers of the levels of PM10 observed in Montevideo during the period. Industrial activity does not seem to affect the concentrations of the pollutant in a statistically significant way.

4.2 Sensitivity and Robustness

We interact each of the air quality variables with a dummy indicating that the mother's maximum level of education is above middle school. We also repeat the analysis with a dummy indicating a level of education of high school or more. Regardless of the indicator of education, we do not find differential effects of PM10 concentration on mothers of different education level.

In a similar analysis, we interact an indicator of public health coverage with the air pollution standards by trimester under the hypothesis that those with public health coverage are of lower socioeconomic status. More specifically, we add interactions between the pollution levels and an indicator variable equal to one if the health center that the mother attended during pregnancy is public, and zero if private. Again, we do not find statistically significant differences between public and private centers in any trimester and for any of the perinatal health outcomes. Nor do we find differences when interacting PM10 with the woman's smoking status. These results are available upon request.

For robustness, we replicate the analysis using data from manual stations in Montevideo. Appendix Table A1 shows the results from a regression of the average level of PM10 from the three manual stations in Montevideo in each trimester of the pregnancy on the perinatal outcomes of interest. (PM10 is defined in tens of μg/m^3). Results are consistent with those in Table 3: we find evidence of a negative and significant effect of PM10 concentration during the third trimester on birth weight. The smaller magnitude of the effect, relative to that in Table 3, could reflect measurement error due to lower precision of estimation in the manual stations.

The other analysis is run only on a subsample of women attending prenatal care clinics in a radio of 2.5 km from one of the three manual monitoring stations (N=1,853). We assign each of these women the air quality of the monitoring station that is nearest the prenatal care clinic (the only geocoding reference available in the data). Our results are for the most part robust to this alternative specification (see Appendix Table A2): PM10 concentration during the third trimester increases the likelihood of LBW and decreases birth weight.

Finally, we conducted some explorations of the effects of other pollutants, such as CO, SO2 and NO2 on birth outcomes. Unfortunately, and as observed in prior literature, the estimates of these effects were less robust, with counterintuitive or ambiguous signs. Results are available upon request.

5. Conclusions

This paper explores the effect of breathable particulate matter with diameter of 10 micrometers or less (PM10) on the likelihood of a premature birth and low birth weight (LBW). We exploit the fact that in 2011 the ashes and dust resulting from the eruption of the Puyehue volcano in Chile increased substantially the exposure to PM10 in Montevideo.

We find that PM10 concentration has statistically significant effects on LBW, birth weight, and prematurity in every trimester of the pregnancy. In particular, we find that a 10 μg/m^3 increase in three-monthly exposure to PM10 during the second and third trimester increases in average the likelihood of PTB by 1.4 and 3.0 percentage points, respectively (17 percent and 30 percent of the average prematurity rate of 8.3). The effect of PM10 on the probability of LBW is driven primarily by an effect on prematurity. Furthermore, our quadratic specification shows that for trimestral averages of PM10 concentrations above 50 μg/m^3, particulate matter becomes detrimental to the fetus at increasing rates. The highest adverse effects occur during the third trimester. Moreover, in the case of our linear specification, the exposure to PM10 during the first trimester is associated with beneficial birth outcomes. A possible explanation is that higher levels of PM10 in the first trimester could lead to spontaneous abortions.

Our research provides rigorous new evidence of the association between PM10 and perinatal health in a developing country, and in particular in Latin America, where the literature is scarce. In addition, we analyze the effects of short exposures to high levels of particulate matter in a city characterized by good air quality. In this sense, our study differs from others in its focus on the immediate, rather than the cumulative, effects of exposure to pollutants on health at birth. This refinement could be important in a climate change scenario. Recent research shows strong evidence of a correlation between heat waves and an increase in concentrations of PM10 (Katsouyanni and Analitis, 2009, and Papanastasiou et al., 2013). Understanding the health costs of shocks such as heat waves is important if natural phenomena affecting air quality are to become more prevalent in the future. Finally, our paper informs policy makers about the importance of taking measures to reduce the exposure of pregnant women to acute PM10 episodes and of developing knowledge to treat the negative effects of these episodes.

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Table 1. Descriptive Statistics (N=60,102)

	Mean	Std. Dev.
Perinatal outcomes		
LBW	0.074	0.261
Birth weight	3,264.425	547.963
PTB	0.083	0.276
Air quality		
PM10 1st trimester of pregnancy (in tens of µg/m³)	3.289	1.648
PM10 2nd trimester of pregnancy (in tens of µg/m³)	3.313	1.643
PM10 3rd trimester of pregnancy (in tens of µg/m³)	3.246	1.673
Air quality in pregnancies exposed to the Puyehue		
PM10 3rd trimester in pregnancies exposed to Puyehue	5.795	0.960
% days that PM10 >50 during pregnancy exposed to Puyehue	0.294	0.150
Air quality in pregnancies not exposed to the Puyehue		
PM10 3rd trimester in pregnancies not exposed to Puyehue	2.370	0.955
% days that PM10 >50 during pregnancy not exposed to Puyehue	0.069	0.062
Controls		
Age <20	0.164	0.370
Age 20-34	0.685	0.464
Age 35-39	0.124	0.330
Age>39	0.027	0.162
Education: completed high school	0.315	0.464
Education: completed middle school	0.300	0.458
Education: did not complete middle school	0.385	0.487
Marital Status: Married	0.270	0.444
Marital Status: Cohabitation	0.544	0.498
Marital Status: Single	0.177	0.382
Marital Status: Other	0.009	0.093
Pre-eclampsia	0.032	0.176
Pre-eclampsia missing	0.098	0.297
Eclampsia	0.002	0.041
Eclampsia missing	0.099	0.299
Hypertension	0.022	0.147
Hypertension missing	0.098	0.297
Smoker	0.239	0.426
Smoking status missing	0.008	0.089
Male	0.510	0.500
Gestational week of initation of prenatal care	12.365	7.340
Average precipitation rate in pregnancy	2.996	1.060
Average temperature in pregnancy	17.161	4.122
Average wind intensity in pregnancy	10.430	1.267
Average humidity in pregnancy	72.506	4.098
Average air pressure in pregnancy	1,015.332	2.595
Average real income per capita	157.729	6.998

Table 2. Overall, Within and Between-Stations Variation in PM10

Trimester averages from three manual monitoring stations in Montevideo (2009-2012)

	Mean	Std. dev.	Min	Max	Observations
Overall	35.142	14.694	15.701	112.500	N = 108
Between		5.496	25.340	41.589	n = 7
Within		13.977	12.436	110.740	T-bar = 15.429

Table 3. Linear Marginal Effects of Average Exposure to PM10 on Birth Outcomes

	LBW (Marginal Effects)	Birth weight	LBW adjusted for gestational age at birth (Marginal Effects)	Birth weight adjusted for gestational age at birth	Prematurity (Marginal Effects)
	(1)	(2)	(3)	(4)	(5)
Mean pm10 1st trimester of pregnancy (in tens of µg/m³)	-0.017***	42.065***	0.002	-0.111	-0.020***
	(0.003)	(5.477)	(0.002)	(3.400)	(0.003)
Mean pm10: 2nd trimester of pregnancy (in tens of µg/m³)	0.010***	-22.125***	-0.002	5.858*	0.014***
	(0.003)	(5.518)	(0.002)	(3.488)	(0.003)
Mean pm10: 3rd trimester of pregnancy (in tens of µg/m³)	0.022***	-56.995***	0.001	-9.219*	0.030***
	(0.005)	(9.694)	(0.003)	(4.897)	(0.006)
Weeks of gestation at birth	No	No	Yes	Yes	No
Age, education, civil status	Yes	Yes	Yes	Yes	Yes
Pregnancy conditions (syphilis, hypertension, preeclampsia, eclampsia)	Yes	Yes	Yes	Yes	Yes
Smoker	Yes	Yes	Yes	Yes	Yes
Weeks of gestation at initiation of prenatal care	Yes	Yes	Yes	Yes	Yes
Weather (temperature, rain, humidity, air pressure, wind)	Yes	Yes	Yes	Yes	Yes
Time trend (quadratic)	Yes	Yes	Yes	Yes	Yes
Prenatal care center fixed effects	Yes	Yes	Yes	Yes	Yes
Month of gestation fixed effects	Yes	Yes	Yes	Yes	Yes
Constant	Yes	Yes	Yes	Yes	Yes

Coefficients and robust standard errors in parentheses. * p<.1, ** p<.05, *** p<.01; N=60102; All regressions are run using ordinary least squares.

Table 4. Quadratic Marginal Effects of Average Exposure to PM10 on Birth Outcomes

	LBW (Marginal Effects)	Birth weight	LBW adjusted for gestational age at birth (Marginal Effects)	Birth weight adjusted for gestational age at birth	Prematur-ity (Marginal Effects)
	(1)	(2)	(3)	(4)	(5)
Mean pm10 1st trimester of pregnancy (in tens of µg/m³)	-0.030**	90.935***	0.014*	-9.965	-0.037***
	(0.012)	(24.753)	(0.009)	(16.220)	(0.013)
Mean pm10 1st trimester of pregnancy squared	0.003**	-8.786***	-0.001	1.131	0.004**
	(0.001)	(2.895)	(0.001)	(1.926)	(0.002)
Mean pm10: 2nd trimester of pregnancy (in tens of µg/m³)	-0.070***	146.251***	-0.011	10.663	-0.099***
	(0.011)	(22.192)	(0.007)	(14.861)	(0.012)
Mean pm10 2nd trimester of pregnancy squared	0.012***	-24.771***	0.001	-0.516	0.016***
	(0.001)	(2.650)	(0.001)	(1.756)	(0.001)
Mean pm10: 3rd trimester of pregnancy (in tens of µg/m³)	-0.166***	315.692***	-0.025***	-4.168	-0.190***
	(0.011)	(20.029)	(0.007)	(11.633)	(0.012)
Mean pm10 3rd trimester of pregnancy squared	0.023***	-45.835***	0.003***	-0.644	0.027***
	(0.001)	(2.382)	(0.001)	(1.294)	(0.001)
Weeks of gestation at birth	No	No	Yes	Yes	No
Age, education, civil status	Yes	Yes	Yes	Yes	Yes
Pregnancy conditions (syphilis, hypertension, preeclampsia)	Yes	Yes	Yes	Yes	Yes
Smoker	Yes	Yes	Yes	Yes	Yes
Weeks of gestation at initiation of prenatal car	Yes	Yes	Yes	Yes	Yes
Weather (temperature, rain, humidity, air pressure, wind)	Yes	Yes	Yes	Yes	Yes
Time trend (quadratic)	Yes	Yes	Yes	Yes	Yes
Prenatal care center fixed effects	Yes	Yes	Yes	Yes	Yes
Month of gestation fixed effects	Yes	Yes	Yes	Yes	Yes
Constant	Yes	Yes	Yes	Yes	Yes

Coefficients and robust standard errors in parentheses. * p<.1, ** p<.05, *** p<.01. N=60102; All regressions are run using ordinary least squares.

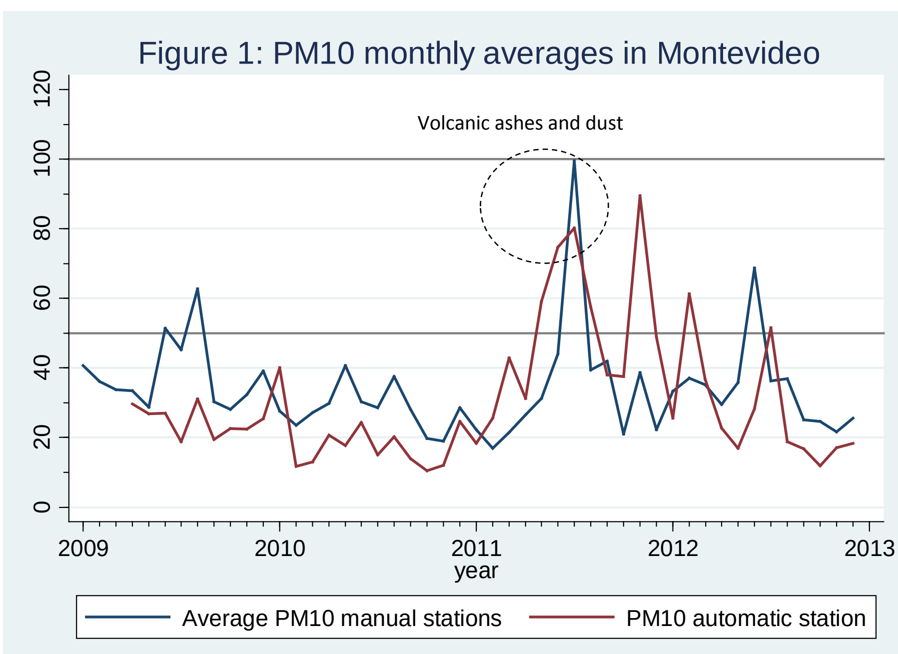
Table 5. Marginal Effects of Average PM10 on LBW, Birth Weight and Prematurity, by Trimester, for Selected Levels of PM10

	First trimester			Second trimester			Third trimester		
PM10 (in tens of µg/m³)	Low birth weight	Birth weight	Prematurity	Low birth weight	Birth weight	Prematurity	Low birth weight	Birth weight	Prematurity
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
2	-0.018***	55.789***	-0.022***	-0.023***	47.166***	-0.035***	-0.073***	132.351***	-0.082***
	(0.007)	(13.695)	(0.007)	(0.006)	(12.294)	(0.007)	(0.007)	(12.332)	(0.007)
3	-0.012***	38.217***	-0.014***	0.001	-2.377	-0.003	-0.027***	40.681***	-0.027***
	(0.004)	(8.693)	(0.005)	(0.004)	(8.047)	(0.004)	(0.005)	(9.779)	(0.006)
4	-0.006**	20.644***	-0.006**	0.024***	-51.919***	0.029***	0.019***	-50.990***	0.027***
	(0.003)	(5.535)	(0.003)	(0.003)	(5.876)	(0.003)	(0.005)	(9.196)	(0.005)
5	-0.000	3.072	0.001	0.048***	-101.462***	0.062***	0.065***	-142.660***	0.082***
	(0.004)	(7.263)	(0.004)	(0.004)	(7.778)	(0.004)	(0.006)	(10.904)	(0.007)
6	0.006	-14.501	0.009	0.072***	-151.004***	0.094***	0.111***	-234.331***	0.136***
	(0.006)	(11.914)	(0.006)	(0.006)	(11.944)	(0.007)	(0.008)	(14.093)	(0.009)
7	0.012	-32.074*	0.017*	0.096***	-200.547***	0.126***	0.158***	-326.001***	0.191***
	(0.008)	(17.268)	(0.009)	(0.008)	(16.763)	(0.009)	(0.010)	(17.993)	(0.011)
8	0.018	-49.646**	0.024**	0.119***	-250.090***	0.158***	0.204***	-417.672***	0.245***
	(0.011)	(22.836)	(0.012)	(0.011)	(21.806)	(0.012)	(0.012)	(22.232)	(0.014)
9	0.024*	-67.219**	0.032**	0.143***	-299.632***	0.190***	0.250***	-509.342***	0.300***
	(0.014)	(28.492)	(0.015)	(0.013)	(26.948)	(0.015)	(0.014)	(26.648)	(0.017)
10	0.030*	-84.791**	0.040**	0.167***	-349.175***	0.222***	0.296***	-601.013***	0.354***
	(0.017)	(34.194)	(0.018)	(0.016)	(32.142)	(0.017)	(0.017)	(31.168)	(0.019)

Table 6. Effects of Economic Activity, Weather, and the Puyehue Eruption on Monthly PM10 Averages in Montevideo (2010-2012)

OLS regression (N=36)	Monthly PM10 averages
Industrial activity	0.195
	(0.381)
Oil refinery	-0.364
	(0.787)
Power plant activity	0.299
	(0.516)
Puyehue eruption	43.668***
	(10.328)
Precipitations	-0.608
	(1.297)
Wind intensity	-1.878
	(1.678)
Constant	28.949
	(57.257)

Coefficients and robust standard errors in parentheses. * p<.1, ** p<.05, *** p<.01



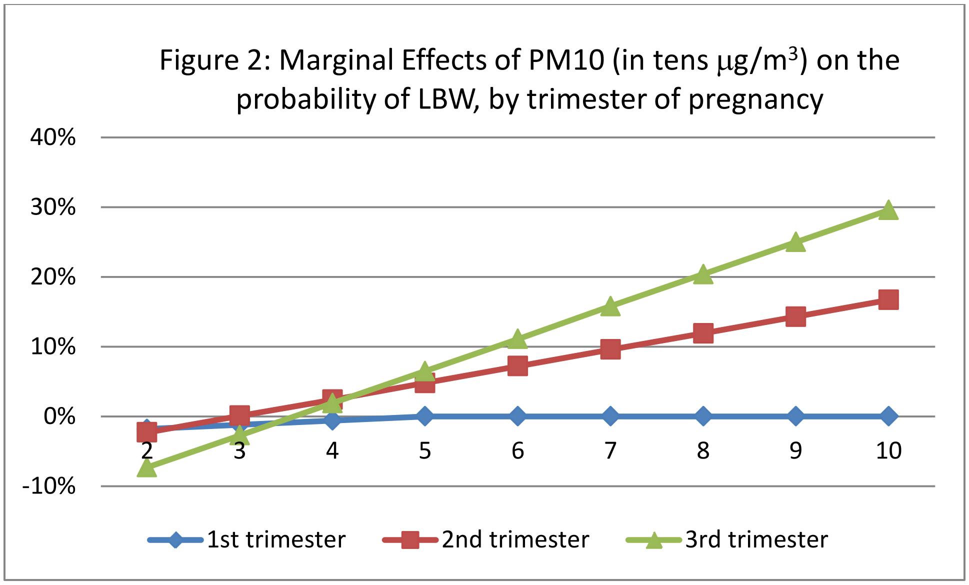


Figure 2: Marginal Effects of PM10 (in tens μg/m3) on the probability of LBW, by trimester of pregnancy
40%
30%
20%
10%
0%
-10%
2
3
4
5
6
7
8
9
10
1st trimester
2nd trimester
3rd trimester

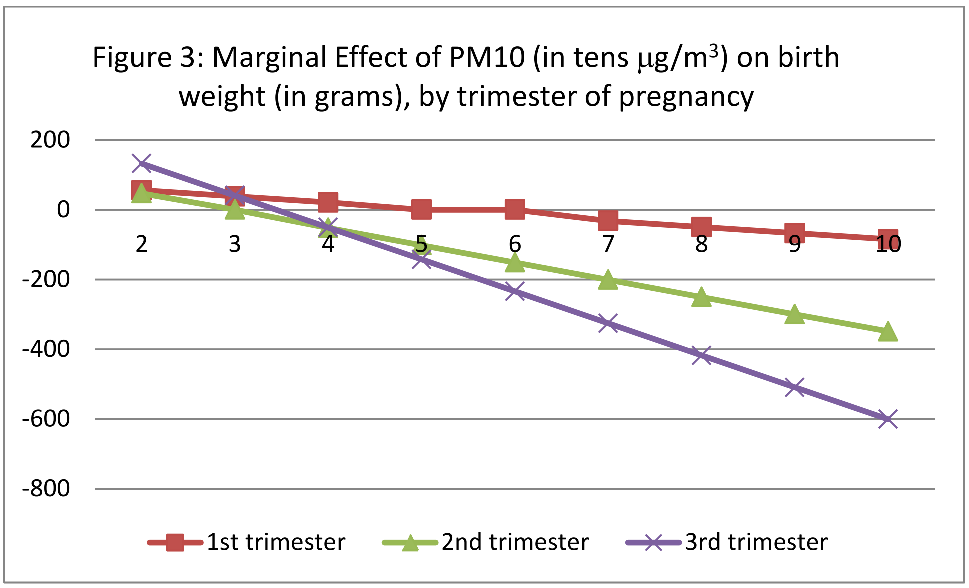


Figure 3: Marginal Effect of PM10 (in tens μg/m3) on birth weight (in grams), by trimester of pregnancy
200
0
-200
-400
-600
-800
2
3
4
5
6
7
8
9
10
1st trimester
2nd trimester
3rd trimester

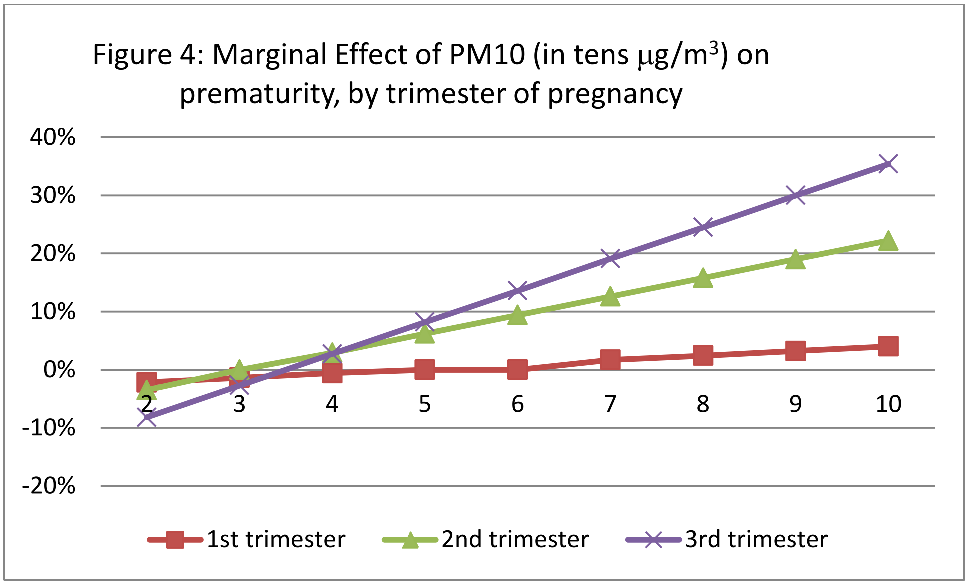


Figure 4: Marginal Effect of PM10 (in tens μg/m3) on prematurity, by trimester of pregnancy
40%
30%
20%
10%
0%
-10%
-20%
2
3
4
5
6
7
8
9
10
1st trimester
2nd trimester
3rd trimester

Appendix

Appendix Table A1. Marginal Effects of Average PM10 Concentration in Manual Stations on Perinatal Health, Temporal Analysis Only

	Logit	OLS	Logit	OLS	Logit
	LBW	Birth weight	LBW adjusting for gestational age	Birth weight adjusting for gestational age at birth	Pre-term birth
	(1)	(2)	(3)	(4)	(5)
Avg PM10 manual stations 1st trimester	-0.001	-2.955	0.001	0.760	-0.003
(in tens of µg/m³)	(0.003)	(6.432)	(0.002)	(4.448)	(0.003)
Avg PM10 manual stations 2nd trimester	-0.003	8.416	0.000	-1.629	-0.005
(in tens of µg/m³)	(0.003)	(6.206)	(0.002)	(3.892)	(0.003)
Avg PM10 manual stations 3rd trimester	0.006*	-14.802**	0.001	-3.704	0.007*
(in tens of µg/m³)	(0.003)	(7.499)	(0.002)	(4.517)	(0.004)

Notes: Coefficients and robust standard errors in parentheses; * p<.1, ** p<.05, *** p<.01. Columns (3) and (4) control for weeks of gestation at birth. All regressions adjust for age, education, civil status, pregnancy conditions (hypertension, eclampsia preeclampsia), smoker status, weeks of gestation at initiation of prenatal care, income per capita, weather (temperature, rain, humidity, air pressure, wind), a quadratic time trend), prenatal care center fixed effects and month of gestation fixed effects. N=60,026.

Appendix Table A2. Marginal Effects of Average PM10 Concentration in Manual Stations on Perinatal Health, Spatio-Temporal Analysis

	Logit	OLS	Logit	OLS	Logit
	LBW	Birth weight	LBW adjusting for gestational age	Birth weight adjusting for gestational age at birth	Pre-term birth
	(1)	(2)	(3)	(4)	(5)
Avg PM10 manual stations 1st trimester	0.016	31.350	0.021**	-40.357*	-0.018
(in tens of µg/m³)	(0.019)	(34.522)	(0.011)	(23.925)	(0.017)
Avg PM10 manual stations 2nd trimester	0.022	-34.548	0.001	28.170	0.031**
(in tens of µg/m³)	(0.013)	(23.905)	(0.011)	(18.007)	(0.014)
Avg PM10 manual stations 3rd trimester	0.036*	-75.169**	0.010	-23.976	0.033*
(in tens of µg/m³)	(0.019)	(35.779)	(0.008)	(17.837)	(0.019)

Notes: Coefficients and robust standard errors in parentheses; * p<.1, ** p<.05, *** p<.01. Columns (3) and (4) control for weeks of gestation at birth. All regressions adjust for age, education, civil status, pregnancy conditions (syphilis, hypertension, preeclampsia), smoker status, weeks of gestation at initiation of prenatal care, income per capita, weather (temperature, rain, humidity, air pressure, wind), a quadratic time trend), prenatal care center fixed effects and month of gestation fixed effects. N=1,853.