Exposures to Particulate Matter from the Eruptions of the Puyehue Volcano and Birth Outcomes in Montevideo, Uruguay

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Running title: Air pollution and birth outcomes

Acknowledgments: We thank Pablo Franco, Andrea de Nigris, Katharina Janke, Sebastián Miller, and attendants to the 2013 Central Bank Economic Conference in Uruguay, the University of Montevideo Department of Economics 2014 Seminar Series, and the 5th ASHEcon Conference at Los Angeles (2014), for valuable comments and suggestions. We acknowledge financial support from the Inter-American Development Bank (IADB), grant RGK1219 "Advancing the Research Agenda in Climate Change and The Environment". All opinions and errors remain our own.

The authors declare that they have no actual or potential financial interests.

Abstract

Background: The ashes and dust resulting from the 2011 eruptions of the Puyehue volcano in Chile more than doubled monthly averages of PM10 concentrations in Montevideo, Uruguay. Few studies have taken advantage of natural experiments to assess the relationship between ambient air pollutant concentrations and birth outcomes.

Objectives: This study explores the effect of particulate matter with diameter of 10 micrometers or less (PM10) on perinatal outcomes in Uruguay, a middle-income country in South America with levels of PM10 that in general do not exceed the recommended thresholds. The analyzed outcomes are preterm birth, term birth weight, and term low birth weight.

Methods: We take advantage of the sharp variation in PM10 concentrations due to the Puyehue eruptions to estimate the associations between mother's exposure to PM10 in each trimester of pregnancy and perinatal outcomes. We use birth registries for 2010-2013 and control for covariates, including maternal and pregnancy characteristics, weather, co-pollutants, and calendar quarter and hospital indicators.

Results: A 10-$\mu g/m^3$ increase in exposure to PM10 during the third trimester was associated with a higher likelihood of a preterm birth (OR = 1.10; CI: 1.03, 1.19). The association was robust to different model specifications, and increased with categorical exposure levels [OR for third trimester PM10 ≥ 70 vs. < 30 $\mu g/m^3$ = 5.24 (95% CI: 3.40, 8.08)]. Exposures were not consistently associated with birth weight or preterm birth among term births, though second trimester exposures were associated with higher birth weight, contrary to expectations.

Conclusions: Taking advantage of a natural experiment, we found evidence that exposure to high levels of PM10 during the third trimester of pregnancy may have increased preterm births among women in Montevideo, Uruguay.

Introduction

The Puyehue Cordon Caulle volcanic complex in Chile experienced a series of eruptions between June and November of 2011. Following these events, clouds of dust covered the city of Montevideo. During June and July, daily concentrations of particulate matter of up to 10 micrometers (PM10) in Montevideo exceeded the WHO 24-hour mean guideline of 50 $\mu g/m^3$ (WHO 2006) in 60% of the days, and were higher than 100 $\mu g/m^3$ in 30% of the days. The eruption in November caused a similar increase in PM10 concentrations. In this paper we take advantage of this natural experiment to analyze the association between exposure to PM10 and preterm birth (PTB), term birth weight (BW) and term low birth weight (LBW).

LBW and PTB are commonly used as proxies for infant health and are markers for poor health during the life course (McCormick 1985; Petrou et al. 2001; Boardman et al. 2002; Black et al. 2007; Oreopoulos et al. 2008). LBW has been associated with higher morbidity and lifetime health costs, as well as lower academic achievement, lower income, and early mortality (Behrman and Rosenzweig 2004; Almond et al. 2005; Royer 2009; Currie 2009; Rosenzweig and Zhang 2013; Figlio et al. 2014). Moreover, there is evidence of a strong intergenerational correlation in the BW of mothers and children (Currie and Madrian 1999; Grossman 2000; Case et al. 2004; Currie and Moretti 2005; Currie 2009).

While many studies have analyzed the association between ambient air pollutant concentrations and birth outcomes (Šrám et al. 2005; Currie et al. 2009; Woodruff et al. 2009; Parker et al. 2011; Stieb et al. 2012; Dadvand et al. 2013), only a few (Parker et al. 2008; Rich et al. 2015; Huang et al. 2015) have approached the issue by using a natural experiment. (Parker et al. 2008) compared pregnancies exposed to the Utah Valley Steel Mill closure that occurred between mid-1986 and mid-1987 to pregnancies in pre-and post-closure periods. They found that mothers who were pregnant around the time of the closure of the mill were less likely to deliver prematurely than mothers who were pregnant before or after the mill closure. Similarly, (Rich et al. 2015) compared pregnancies exposed to the air pollution declines during the 2008 Beijing Olympics to pregnancies pre-and post- Olympic games. Their results showed that exposure to lower levels of air pollution late in pregnancy were associated with higher BW. (Huang et al. 2015) also took advantage of the reduction in air pollution during the 2008 Olympics in Beijing, but found no relationship between PM10 concentration and term BW or PTB. Other studies using natural experiments to assess the effects of pollution on perinatal outcomes are (Chay and Greenstone 2003a, 2003b) and (Currie and Walker 2011). However, none of them focused on the effects of mother's exposure to PM10 on birth outcomes.

Our study contributes to this literature by estimating associations between birth outcomes and variation in pollution resulting from a volcano eruption, a natural and completely unexpected event. It is also one of a few studies to report the association between PM10 and birth outcomes in Latin America.

Methods

Data

Pregnancy and delivery data

We analyzed live births that took place in Montevideo during 2010-2013 and that were registered in the Perinatal Information System (CPHD, PAHO/ WHO, 1999). The Perinatal Information System is a mandatory electronic registry of perinatal histories covering about 98% of all pregnancies in the country. Because the data were anonymous, approval from a review board was not required.

The outcomes of interest were PTB, BW for full term pregnancies, and LBW for full term pregnancies. We defined a PTB as a delivery occurring before the 37^{th} week of gestation. BW was measured in grams. LBW was a binary variable that took the value of 1 if the BW was 2500 grams or less, and 0 otherwise.

We addressed potential confounding by adjusting for several maternal characteristics that may contribute to maternal and pregnancy heterogeneity: mother's age (<20, 20–34, 35–39, ≥40 years), education level (less than middle school, middle school completed, or high school completed), marital status (common law, married, single, other), eclampsia or hypertension during the pregnancy (separate variables based on birth record information, yes/no), maternal smoking during pregnancy (yes/no), body mass index prior to pregnancy (based on mother's recall at first visit; underweight: BMI <18.5, normal: 18.5≤BMI<25, overweight: 25≤BMI<30, obese: BMI≥30), parity (continuous), onset of prenatal care (gestational week, continuous), and the child's gender.

Our analysis also accounted for health-care heterogeneity by adjusting for 22 binary indicators for the 23 hospitals in the city. Of these, 10 were public, covering the poorest fraction of the population (40% of all deliveries) and the rest were private hospitals associated with health maintenance organizations that provide services to privately insured individuals or to workers in the formal labor market and their dependents through the national social insurance (National Integrated Health System).

We dropped multiple births and births with BW below 300 grams or above 8000 grams. To avoid the problem of fixed cohort bias raised by (Strand et al. 2011), we restricted our sample to pregnancies conceived between 1^{st} June 2009 and April 1^{st} 2013. We were not able to distinguish multiple pregnancies to the same mother; therefore eligible births may include more than one pregnancy in the same woman.

Air quality data

The air quality data came from the Environmental Control and Quality Evaluation Service of the Municipal Government of Montevideo. This office is in charge of the city's air quality monitoring network. In 2009 the network incorporated an automatic station in the area of Colón, North of Montevideo, measuring air quality (PM10, SO_2, CO, and, NO_2) on an hourly basis. This was the only automatic monitoring station in Montevideo operating throughout the full period of analysis (2009-2013).

While three other manual stations in the city collected data on PM10 between 2009 and 2013, we chose not to work with these other sources for two reasons. First, because samples in the manual stations were obtained every 6 days and were more likely to miss extreme episodes, such as days with abnormal levels of ashes (IMM 2016). Second, our analysis of data from these manual stations (available upon request), shows that most of the variation in PM10 levels occured over time for the full city, rather than between city areas. Unreported analysis of variance for the period 2009-2013 shows that the variation in PM10 resulting from the volcanic eruption was almost 3 times higher than the intra neighborhood variation in air quality in Montevideo.

Our variable of interest is ambient air 24-hour mean concentration of PM10, averaged at the trimester-of-pregnancy level. Specifically, we calculated the week of initiation of the pregnancy by subtracting the gestational age at birth, as assessed by the obstetrician at delivery, from the date of birth, and then adding two weeks to account for the difference between gestational age (which is based on the last menstrual period) and the date of conception. For each pregnancy, we matched each week with the corresponding average PM10 for that week, and then computed the average exposure to PM10 in the first, second, and third trimesters of pregnancy. The first trimester runs from conception to week 13, and the second trimester from week 14 to week 27. Exposure to PM10 during the third trimester depends on the term of gestation. When analyzing the probability of a PTB, we computed the third trimester values by averaging PM10 levels between gestation week 28 and gestation week 36 if the pregnancy reached full term, or between gestation week 28 and the week of delivery if the birth occurred prior to week 37. When analyzing outcomes for full term births (BW and LBW) we considered the average exposure to PM10 for the full third trimester.

Weather data and other controls

We obtained 24-hour mean averages of temperature (in degrees Celsius), air pressure (in hPa), windspeed (in meters per second), and humidity (in percentage) from three weather-monitoring stations of the National Institute of Meteorology located in the East, North, and West of Montevideo (Carrasco, Prado, and Melilla). We also obtained from these same stations the accumulated level of precipitation over 24 hours, measured in mm per square meter. For each weather variable we averaged out these measures across the three stations and constructed trimester-of-pregnancy-specific averages following the same procedure as with PM10.

Statistical analysis

Estimation procedure

We estimated the associations between a pregnant mother's average exposure to PM10 in each trimester of her pregnancy and three perinatal outcomes: PTB, BW, and LBW. We considered all births when analyzing PTB, but only full term births when the outcomes were BW and LBW. By restricting the analysis of these two outcomes to non-premature pregnancies, we sought to isolate potential associations between PM10 and intrauterine growth retardation. Our identification strategy relied on the exogenous variation of PM10 concentration in Montevideo that resulted from the Puyehue ashes.

We estimated associations between exposure to PM10 during the pregnancy and BW with Ordinary Least Squares, and used logistic models for the dichotomous outcomes (PTB, LBW). We set the statistical significance level (α) at 0.05. For PM10 as a continuous variable, our model took the form:

$$Y = f(\alpha + \beta_1 PM10\_T1 + \beta_2 PM10\_T2 + \beta_3 PM10\_T3 + \delta X + \gamma Z + \lambda \mu + \phi Q_t) \qquad [1]$$

where Y is PTB, LBW, or BW; and f(.) is a linear function when the outcome is BW and a logistic function when analyzing PTB or LBW. We included all births when analyzing PTB, but only full term births when the outcome was BW or LBW. PM10_T1, PM10_T2 and PM10_T3 represent average exposures to PM10 during the 1^{st}, 2^{nd}, and 3^{rd} trimester, respectively. The vector X represents maternal covariates, Z represents the five weather variables in each trimester (15 variables total), and μ represents the 22 indicator variables for the 23 prenatal care centers in the study area. In addition, we adjusted for Qt, a vector of 15 indicator variables for the possible 16 combinations of calendar quarter and year of conception in the sample (the earliest date of conception in our data was June 2009 and the latest March 2013). The latter captures underlying trends and seasonality in perinatal outcomes (Currie and Schwandt 2013).

In a second specification, for each trimester t we modeled three dichotomous indicator variables for PM10 categorized as 30–49 µg/m3 (PM30_49t), 50–69 µg/m3 (PM50_69t), and ≥ 70 µg/m3 (PM70t), with PM10 <30 µg/m3 serving as the reference exposure category. We refer to the estimations resulting from this specification as the categorical PM10 analysis.

We conducted, in addition, several robustness tests. Because the consistency of our estimates relies on the exogeneity of PM10 variation over time, we run two additional regressions that controlled for potential confounders. The first regression added a set of adjustors to the core categorical regression that were potentially associated with the concentration levels of PM10. These included the level of activity of two thermal plants, measured in megawatt-hours (MWh), and obtained from the Electric Market Administration Office, and the production volume of the oil refinery, a production index with base 2006=100 constructed by the National Institute of Statistics. For both measures, we computed trimester-of-pregnancy-specific averages on the basis of the available monthly measures.

The second regression added controls for NO_2 (in µg/m3), SO_2 (in µg/m3) and CO (in µg/m3) to the core categorical analysis. These co-pollutants were averaged at the trimester of pregnancy level in the same way as the PM10 and weather variables. We run regressions controlling first for one co-pollutant at a time, and then adding the three in the same estimation. We did not have complete data on CO, SO_2, and NO_2. 24-hour data was missing on 0.17% of the days for CO, on 10% of the days for NO_2, and on 6% of the days for SO_2. Because there were no large periods without data we disregarded these days with missing values when constructing averages at the trimester of pregnancy level. By doing so, we had no missing data on trimester averages of these copollutants for full term births. However, for a few number of deliveries with low gestational age, we had some missing values for the third trimester. In particular, CO was missing for 31 observations, NO_2 was missing for 51 observations and SO_2 was missing for 5 observations. This explains why the number of observations in the analyses of PTB varies when adjusting for different copollutants, whereas the number of observations is the same, regardless of the copollutant, in the analyses of BW and LBW.

A third sensitivity check addresses the issue of missing values on eclampsia, hypertension, parity, and smoking. In the core analysis we imputed the corresponding mean value to the observations with missing data on one or more of these variables, and added a dichotomous indicator equal to 1 when the observation had a missing value on the variable and 0 otherwise. The only variables with missing data were eclampsia, hypertension, parity, and smoking. For categorical variables, we imputed the average proportion of women with the characteristic. We used one separate dichotomous indicator of missing data for each of the four covariates. The purpose of these indicators was to absorb any differential variation on observations with missing data, without having to rely on the artificially imputed value (which was constant across all observations with a missing value). The estimates could be biased if women with missing observations on these variables were different from other women, and the fraction of these women was changing over time. We explored this issue by running the analysis only for observations without missing values on eclampsia, hypertension, parity, and smoking.

Fourth, in order to assess the sensitivity to the reference group used for comparison, we first restricted our estimation to pregnancies with a date of delivery before or during the volcano eruptions, and then to pregnancies with a conception date after the first eruption (restricting in this case the sample to pregnancies exposed to the ashes and pregnancies post-eruption). We also estimated associations with PM10 (categorical and continuous) for pregnancies that were not exposed to the volcano eruptions (deliveries before June 8th 2011 and pregnancies with a date of conception after December 30th 2012). During these periods only 156 pregnancies had exposures $\geq 50\ \mu g/m^3$ in any trimester.

Fifth, the inclusion of several variables in the same regression measuring pollution and weather by trimester raises the challenge of multicollinearity and its potential consequences on the precision of standard errors. To test for this possibility, we followed (Bell et al. 2007) and used residuals of trimester averages regressed on the average of a reference trimester. For simplicity, we conducted this robustness check only on the specification using a single average by trimester. For example, we selected the 1st trimester as the reference trimester and then regressed PM10 (and weather) averages for the second and third trimester on the 1st trimester. We rerun the estimations using residuals of the instrumental regressions for the second and third trimesters, as well as the average for the reference category. We repeated this exercise alternating the reference trimester.

Results

Table 1 provides descriptive statistics for the main variables in the analysis by time period (before, during, and after the Puyehue eruption). The proportion of preterm births in the full period is 8%; 7% occurred between the 32nd and 36th weeks of gestation, and 1% took place between gestational weeks 28 and 31. Among full term births, 2.7% were low weight. The average weight for a full term baby was 3,354 grams. Almost 70% of women belonged to the 20-34 age range, 32% were high school graduates, and 37% had not completed middle school. The majority of mothers (54%) lived under common law, 27% were married, and 18% were single. Almost one out of four women reported smoking during the pregnancy (missing data for 0.6% of the sample). The majority of women initiated prenatal care during the 12th week of gestation. Overall, our data had 79,328 observations on pregnancies, 26,266 of which were exposed to high levels of particulate matter in June, July or November of 2011 due to the ashes from the Puyehue eruption. We observed 24,906 pregnancies with delivery dates prior to the volcano eruption and 28,156 pregnancies with conception dates after the eruption.

When averaged at the trimester level, the standard deviation of PM10 over time (i.e., within stations) was 14 while the standard deviation between stations was 5.5. Figure 1 shows monthly averages of PM10 in Montevideo and highlights the dates when the volcanic ashes from the Puyehue arrived in the city. The mean level of PM10 during the 1st trimester was 21.2 μg/m³ (± 5.9) for pregnancies not exposed to the Puyehue ashes and 46 μg/m³ (± 17.4) for pregnancies exposed to the ashes (see Table 1). Averages for the second and third trimesters (not shown) were similar to the first trimester averages shown in Table 1. Table 1 shows also that almost half of the pregnancies during the Puyehue period were exposed to trimester-average levels of PM10 above 50 μg/m³. On the contrary, none of the pregnancies before or after the eruptions were exposed to trimester-average levels of PM10 this high.

Table 1 shows also descriptive statistics for other pollutants, including CO, NO_2, and SO2. As in the case of PM10, average levels of CO increased during the volcano period and then returned to prior levels. There was no evidence of increases in the levels of NO_2 and SO_2. Furthermore, we did not find correlations of magnitude between PM10 and other pollutants. Correlation coefficients change signs in the different periods of analysis, suggesting a noisy relationship between the pollutants.

Continuous PM10 Analysis

We found a positive association between average PM10 exposure during the third trimester and PTB (Table 2). A 10-μg/m³ increase in average PM10 during the third trimester was associated with a 10% increase in the odds of PTB (OR = 1.10; 95% CI: 1.03, 1.19). On the other hand, we did not find evidence of adverse associations between PM10 and term BW or term LBW. We did find, however, a positive small association between PM10 concentrations during the second trimester and BW. A 10-μg/m^3 increase in PM10 during the second trimester was associated with a 13 gram higher birth weight among term births (95% CI: 4.07, 22.13).

Categorical PM10 Analysis

PM10 during the third trimester was significantly associated with PTB, with OR = 1.42 (95% CI: 1.07, 1.89) for 50–69 μg/m3 and OR = 5.24 (95% CI: 3.40, 8.08) for ≥ 70 μg/m3 compared with < 30 μg/m3 (Table 3). We also found significant associations between PM10 and PTB in the case of the first and second trimesters, but in these cases odds ratios were less than one: OR = 0.69 (95% CI: 0.47, 1.02) for ≥ 70 μg/m3 in the first trimester, OR = 0.79 (95% CI: 0.64, 0.97) for 30–49 μg/m3 in the second trimester, and OR = 0.76 (95% CI: 0.59, 0.99) for 50–69 μg/m3 in the second trimester, compared with < 30 μg/m3 (Table 3).

The two last rows in Tables 2 and 3 compare the goodness of fit of each model under the Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC). Both criteria suggest that the categorical model fits the data better when the outcome is PTB. The choice is less clear when analyzing term BW and term LBW: the Akaike information criterion indicated that the categorical model fits the data better, whereas the linear model is better according to the BIC criterion.

Sensitivity and Robustness

Supplemental Material, Table S1 depicts the results of the categorical analysis adding controls for the level of activity of two thermal power stations and an oil refinery in Montevideo, which could potentially be correlated with PM10. Results were robust to this expanded set of controls (Table S1).

Supplemental Material, Table S2 shows the results of categorical analysis when adding controls for NO_2, SO_2, and CO averages in each trimester of pregnancy to the set of core controls. The addition of these variables resulted in fewer observations in the analysis of preterm births, due to missing data on third trimester averages of these variables for some women delivering a few days into the third trimester. The association of PTB with 3^{rd} trimester exposure was stronger after adjustment for all three air pollution variables, with OR = 1.67 (95% CI: 1.19, 2.35) for 50–69 µg/m3 (vs. 1.42; 95% CI: 1.07, 1.89 for the default model) and OR = 16.35 (95% CI: 9.26, 28.88) for ≥ 70 µg/m3 (vs. 5.24; 95% CI: 3.40, 8.08 for the default model). On the other hand, we found statistically significant positive associations with PTB and negative associations with BW. For PTB and first trimester PM10, OR = 1.15 (95% CI: 0.87, 1.51) for 50–69 µg/m3 and OR = 1.45 (95% CI: 0.92, 2.26) for ≥ 70 µg/m3 compared with first trimester PM10 < 30 µg/m3. Average birth weight was estimated to be 28g lower (95% CI: –55.58, –1.21) for 50–69 µg/m3 during the first trimester. Other results were similar to those in Table 3. Tables S3-S5 report results when adjusting for one co-pollutant at a time. We found no major qualitative changes, although 3^{rd} trimester effects of PM10 values above 70 $\mu g/m^3$ were higher when only adjusting for CO.

Table S6 shows the results of our third sensitivity check, which ran the analysis only for observations without missing values on eclampsia, hypertension, parity, and smoking. The results were similar to those in the core specification, suggesting that our treatment of missing observations did not compromise the findings.

Supplemental Material, Table S7 shows the results of our estimation when restricting the analysis to pregnancies conceived before or during the volcano eruptions. These were quite similar to those in the categorical core specification (Table 3), in particular for the associations with concentration levels above 70 $\mu g/m^3$. One difference with the core model was the statistically significant and negative association between exposure to PM10 during the 1st trimester and the odds of a PTB (OR = 0.65 (95% CI: 0.47, 0.90) for 30–49 $\mu g/m^3$, OR = 0.61 (95% CI: 0.42, 0.88) for 50–69 $\mu g/m^3$, and OR = 0.57 (95% CI: 0.34, 0.95) for ≥ 70 μg/m3 compared with first trimester PM10 < 30 μg/m3 in Table S7, versus OR = 0.92 (95% CI: 0.78, 1.08) for 30–49 $\mu g/m^3$, OR = 0.85 (95% CI: 0.66, 1.08) for 50–69 $\mu g/m^3$, and OR = 0.69 (95% CI: 0.47, 10.2) for ≥ 70 $\mu g/m^3$ compared with first trimester PM10 < 30 μg/m3 in Table 3).

In Supplemental Material, Table S8 we show results when restricting the analysis to pregnancies with a birth date after the first eruption. Again, the positive association between high levels of concentration of PM10 in the third trimester and PTB was robust to this change in the sample, although the odds ratio was larger for PM10 ≥ 70 µg/m3 (OR = 14.27 (95% CI: 8.49, 23.98) in Table S8, versus OR = 5.24 (95% CI: 3.40, 8.08) in Table 3). We also found some positive associations between high exposures to PM10 concentration in the first trimester and BW.

In Tables S9 and S10 of the Supplementary Material we report associations from analyses that were restricted to pregnancies that were not exposed to the volcano eruptions. The associations between PTB and a 10-µg/m3 increase in PM10 during the third trimester were similar to the complete analysis, but not statistically significant (OR = 1.15; 95% CI: 0.93, 1.42 compared with OR = 1.10; 95% CI: 1.03, 1.19 based on the default model). We found, however, a positive association between PM10 levels between 30 and 49 µg/m3 and PTB (OR = 1.35; CI (95%): 1.03 - 1.77) when estimating the categorical model.

Finally, the association between 3rd trimester PM10 and preterm persisted when we modeled residuals of trimester averages regressed on the average of a reference trimester to account for potential collinearity, as in Bell et al. (2007) (see Supplemental Material, Table S11-S13).

Discussion and Conclusions

This paper explored the effect of PM10 on PTB, and on BW and LBW in full-term pregnancies. We took advantage of 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 found that high levels of PM10 concentration during the third trimester were positively associated with PTB in our study population. In particular, we estimated that an increase of 10-μg/m³ in average of PM10 during the third trimester of pregnancy was associated with a 10% increase in the odds of a PTB (95% CI: 1.03, 1.19). Compared with third trimester PM10 < 30 μg/m³, the odds of PTB in women with third trimester PM10 ≥ 70 μg/m³ was about five times higher (OR = 5.24; 95% CI: 3.40, 8.08). These results were generally robust in terms of sign and statistical significance to alternate specifications that controlled for potentially confounding covariates and used different samples. They are also in line with prior results in the literature. For example, estimates from a meta-analysis conducted by (Stieb et al. 2012) showed a pooled OR of the relationship between third trimester PM10 and PTB of 1.06 (95% CI: 1.03, 1.11) per increase of 20-μg/m^3 of PM10. Also, (Parker et al. 2008) found that a reduction in exposure to pollution due to the closure of a steel mill in Utah valley decreased the likelihood of PTB. While they attributed this finding to decreases in pollution in general, they did not explicitly quantify the relationship between PTB and specific pollutant levels. To our knowledge, ours is the first study using a natural experiment to report a positive and significant association between PM10 and PTB.

Unlike some prior studies (Šrám et al. 2005; Parker et al. 2011; Dadvand 2013; Rich et al. 2015), we did not find adverse associations between PM10 and term BW or term LBW. On the contrary, results for some of our specifications suggest that exposures to high levels of PM10 in the second and third trimesters were associated with increases in BW and decreases in LBW for full term births. Similar results have been reported by (Stieb et al. 2012) and (Edwards et al. 2015). While these findings appear at first sight counterintuitive, they could reflect selection effects. The association between higher exposures to PM10 during the second trimester and increases in BW (as well as decreases in LBW) could be the result of a higher risk of spontaneous abortions. Under this hypothesis, exposure to levels of PM10 above 70 μg during the first weeks of the second trimester (before gestation week 20) would be associated with higher weight at birth only because the healthier babies survive the second 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, there is evidence of statistical associations between ambient air pollutants and spontaneous abortions. (Enkhmaa et al. 2014) correlated fetal deaths with mean monthly levels of various air pollutants by means of regression analysis. They used pollution data from Mongolia and 1219 medical records of women who had a spontaneous abortion in the same country. The authors found a correlation of 80-90%, depending on the pollutant in consideration. (Moridi et al. 2014) investigated the association between spontaneous abortion and ambient pollutants. The authors estimated the mean exposure to pollution for each of 296 women in Iran. They found odd ratios of abortion in the areas with higher concentrations of CO, NO_2, O_3 and PM10 ranging between 0.94 and 1.98 ($P < 0.05$).

On the other hand, a potential explanation for the third trimester results on BW and LBW is that they are selection artifacts derived from the negative effects of PM10 on PTB. If high levels of PM10 trigger preterm births that otherwise would not have occurred, and if these additional preterm births are also those with relative lower weight (i.e. affecting the most vulnerable babies), then BW should increase and LBW should decrease in pregnancies that reach full term. This hypothesis assumes that the selection effect stemming from higher levels of preterm births is sufficiently large to offset any negative effect of PM10 on intrauterine growth.

We believe this paper contributes to the literature on pollution and health in several ways. First, it is one of a few studies to investigate the association between pollution and perinatal health using a natural experiment. Our reliance on PM10 variation associated with the volcano eruption, together with the use of adjustors for individual-level characteristics, delivery hospital effects and weather measures, provides internal validity to the study. In particular, our findings are less subject to the critique that results are driven by selection of poorer populations into polluted areas or determined by unobserved time-trends correlated with pollutant trends. Nevertheless, we cannot rule out the possibility that exposure to PM from the volcano could have differed within the study area in relation to socioeconomic and other factors that might be associated with birth outcomes and that we could not control for.

Second, we study transitory and intense exposures to high levels of particulate matter in a city characterized by good air quality. Traditionally, Montevideo has registered 24-hour mean averages of PM10 that fall below WHO's threshold of 50 μg/m³ (IMM 2008, 2009).. Most other analyses deal with regions exposed to high levels of pollutants. Our results are consistent with the hypothesis that even short and acute exposures have effects on health at birth.

Third, our categorical analysis identifies specific ranges for which PM10 can have particularly severe consequences on public health. It contributes, in this way, to the formulation of concrete recommendations for public action in the management of ambient air emergencies. This includes, for example, issuing notices recommending that pregnant women stay inside during such episodes.

Finally, we provide new evidence of the association between PM10 and perinatal health in a developing country, and in particular in Latin America, where the evidence is scarce (Edwards et al. 2015). This is important because underlying conditions may differ according to the country's level of development, and the effects of pollution may be heterogeneous in these features. In our case, one of such differing conditions may be the maternal education level: more than 30% of the mothers in our sample did not finish middle school. Another condition may be the quality of health services.

Our analysis would be biased if the volcano eruptions were spuriously correlated with changes in the composition of pregnant women over time. Ideally, comparing outcomes for the same mother across her different pregnancies would avoid this problem. Unfortunately we are unable to identify multiple pregnancies by the same mother in our data.

To sum up, our results suggest that exposure to high levels of PM10 during the third trimester increased PTB among residents of Montevideo, a city with episodes of high air pollution levels resulting from eruptions of the Puyehue volcano. However, we did not find associations between these exposures and BW or LBW among full term pregnancies. Future research should gain insight on the physiological mechanisms behind these associations.

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Tables

Table 1: Descriptive statistics, by exposure to Puyehue ashes[a] (n=79,328) [data are n (%) or mean ± SD unless otherwise indicated.]

Characteristic[b]	Before eruption (N=24906)	During eruption (N=26266)	After eruption (N=28156)
Individual-level variables			
Pregnancy outcomes			
Preterm birth (<37 weeks)	2191 (8.8)	2045 (7.8)	2172 (7.7)
Birth weight (gr., full term births only)	3335 (±456)	3361 (±451)	3364 (±452)
Low Birth weight (full term births only)	693 (3.1)	586 (2.4)	660 (2.5)
Maternal age			
Age <20	4098 (16.5)	4260 (16.2)	4845 (17.2)
20<=Age<=34	17239 (69.2)	17864 (68.0)	18932 (67.2)
35<=Age<=39	2932 (11.8)	3407 (13.0)	3587 (12.7)
Age>40	637 (2.6)	735 (2.8)	792 (2.8)
Maternal education			
Less than middle school	9824 (39.4)	9696 (36.9)	10243 (36.4)
Middle school <Edu<High school	7481 (30.0)	7901 (30.1)	8453 (30)
Completed high school	7601 (30.5)	8669 (33)	9460 (33.6)
Maternal marital status			
Common Law	13486 (54.1)	14263 (54.3)	15712 (55.8)
Married	6750 (27.1)	7112 (27.1)	7168 (25.5)
Single	4437 (17.8)	4669 (17.8)	5061 (18.0)
Other marital status	233 (0.9)	222 (0.8)	215 (0.8)
Pregnancy complications			
Eclampsia	47 (0.2)	35 (0.1)	33 (0.1)
Eclampsia missing	3097 (12.4)	2154 (8.2)	1405 (5.0)
Hypertension	572 (2.3)	561 (2.1)	661 (2.3)
Hypertension missing	3048 (12.2)	2127 (8.1)	1382 (4.9)
Mother underweight [c]	1597 (6.4)	1562 (5.9)	1683 (6.0)
Normal body mass index [c]	17215 (69.1)	17886 (68.1)	18659 (66.3)
Mother overweight [c]	4171 (16.7)	4564 (17.4)	5221 (18.5)
Mother obese [c]	1923 (7.7)	2254 (8.6)	2593 (9.2)
Mother smokes	6179 (24.8)	6062 (23.1)	6411 (22.8)
Smoking status missing	288 (1.2)	97 (0.4)	67 (0.2)
Parity	1.15 (±1.33)	1.11 (±1.33)	1.08 (±1.28)
Parity missing	3344 (13.4)	2962 (11.3)	3470 (12.3)
Newborn's gender: male	12582 (50.5)	13401 (51)	14432 (51.3)
Week of initiation of prenatal care [d]	12.93 (±7.55)	11.90 (±7.09)	11.40 (±6.71)
Pollution variables			
First trimester PM10 (μg/m3)	20.4 (±4.2)	45.5 (±17.4)	23.7 (±8.7)
< 30 $\mu g/m^3$	24544 (98.5)	6039 (23.0)	20867 (74.1)
30-49$\mu g/m^3$	362 (1.5)	7937 (30.2)	7289 (25.9)
50-69 $\mu g/m^3$	0 (0)	9768 (37.2)	0 (0)
≥ 70 $\mu g/m^3$	0 (0)	2522 (9.6)	0 (0)
CO 1^{st} trimester (μg/m3)	0.49 (±0.03)	1.14 (±0.64)	0.62 (±0.12)
CO missing in any trimester	30 (0.12)	1 (0.00)	0 (0.00)
NO_2 1^{st} trimester (μg/m3)	30.09 (±9.84)	24.48 (±8.02)	24.65 (±8.58)

NO_2 missing in any trimester	6 (0.02)	45 (0.17)	0 (0.00)
SO_2 1^{st} trimester (μg/m3)	17.93 (±6.30)	11.50 (±5.54)	6.77 (±3.23)
SO_2 missing in any trimester	5 (0.02)	0 (0.00)	0 (0.00)
Weather variables			
Precipitations 1^{st} trimester (mm)[e]	3.68 (±0.91)	2.36 (±0.88)	3.58 (±1.07)
Temperature 1^{st} trimester (°C)[f]	15.89 (±3.96)	18.11 (±4.25)	17.78 (±4.08)
Windspeed 1^{st} trimester (m/s)[f]	14.26 (±0.84)	14.60 (±1.50)	13.43 (±1.59)
Humidity 1^{st} trimester (%)[f]	74.00 (±2.37)	69.81 (±4.03)	73.51 (±4.88)
Atmospheric pressure 1^{st} trimester (hPa) [f]	1015.87 (±2.89)	1014.93 (±2.45)	1014.89 (±2.36)
Correlations between pollutants[g]			
PM10 and SO_2 1^{st} trimester	0.73 (p=0.00)	-0.36 (p=0.00)	0.39 (p=0.00)
PM10 and NO_2 1^{st} trimester	-0.36 (p=0.00)	-0.13 (p=0.00)	-0.27 (p=0.00)
PM10 and CO 1^{st} trimester	-0.34 (p=0.00)	-0.20 (p=0.00)	0.13 (p=0.00)

[a] Pregnancies classified as "Before", "During", and "After" eruption were conceived June 2009–Sept. 2010, Oct. 2010–Nov. 2011, and Dec. 2011–March 2013, respectively

[b] In addition to the above mentioned variables, our analysis adjusts for 22 binary indicators for the 23 hospitals in the country

[c] Underweight: Body Mass Index (BMI) <18.5, normal: 18.5≤BMI<25, overweight: 25≤BMI<30, obese: BMI≥30.

[d] Gestational week, continuous.

[e] Trimester of pregnancy means of 24 hour accumulated precipitations.

[f] Trimester of pregnancy means of 24 hour averages.

[g] Correlation coefficients.

Table 2. Preterm birth (all pregnancies, n = 79,328), and low birth weight (< 2,500 g) and birthweight (g) among term births (n = 72,920) in association with a 10-$\mu g/m^3$ increase in average PM10 during each trimester.

Exposure	Preterm birth OR (95% CI)	Birthweight (g) Coefficient (95% CI)	LBW OR (95% CI)
1st trimester	0.97 (0.91,1.06)	-3.03 (-11.27,5.22)	1.04 (0.93,1.15)
2nd trimester	0.96 (0.89,1.05)	13.10 (4.07,22.13)**	1.01 (0.89,1.15)
3rd trimester	1.10 (1.03,1.19)**	-5.78 (-14.90,3.35)	0.94 (0.81,1.08)
Model fit			
Akaike Information Criterion (AIC)	43,845	1,094,481	17,301
Bayesian Information Criterion (BIC)	44,550	1,095,180	18,000

Adjusted for maternal age, education, marital status, pregnancy conditions, maternal smoking status, and onset of prenatal care; temperature, rain, humidity, air pressure, and windspeed intensity in each trimester of pregnancy; indicators for calendar quarter of gestation; and indicators for prenatal care center. Third trimester values for PM10 and weather variables are averaged across gestation weeks 28 and 36 (or an earlier week if the pregnancy did not reach full term) when the outcome is PTB. In the case of BW or LBW, 3rd trimester averages consider the full length of the trimester until birth. **p<0.01; *p<0.05; # p<0.10.

Table 3. Preterm birth (all pregnancies, n = 79,328), and low birth weight (< 2,500g) and birthweight (g) among term births (n = 72,920) in association with PM10 during each trimester.

Exposure	Preterm birth OR (95% CI)	Birthweight (g) Coefficient (95% CI)	LBW OR (95% CI)
First trimester			
< 30 μg/m^3	REF	REF	REF
30–49 μg/m^3	0.92 (0.780,1.08)	-10.03 (-26.78,6.73)	1.05 (0.83,1.33)
50–69 μg/m^3	0.85 (0.66,1.08)	-3.76 (-28.16,20.64)	0.98 (0.68, 1.40)
> 70 μg/m^3	0.690 (0.47,1.02)#	-24.26 (-70.81,22.29)	1.23 (0.64,2.37)
Second trimester			
< 30 μg/m^3	REF	REF	REF
30–49 μg/m^3	0.79 (0.64,0.97)*	16.83 (-2.49,36.15)#	0.98 (0.74,1.29)
50–69 μg/m^3	0.76 (0.59,0.99)*	31.28 (1.89,60.67)*	1.14 (0.74,1.74)
> 70 μg/m^3	0.86 (0.58,1.28)	103.98 (60.89,147.06)**	0.77 (0.41,1.45)
Third trimester			
< 30 μg/m^3	REF	REF	REF
30–49 μg/m^3	1.00 (0.85,1.17)	-7.96 (-26.02,10.10)	0.83 (0.63, 1.08)
50–69 μg/m^3	1.42 (1.07,1.89)*	57.55 (29.24,85.86)**	0.52 (0.35,0.78)**
> 70 μg/m^3	5.24 (3.40,8.08)**	17.89 (-24.55, 60.34)	0.78 (0.43,1.42)
Model fit			
Akaike Information	43,741	1,094,438	17,298
Bayesian Information	44,502	1,095,192	18,052

Adjusted for maternal age, education, marital status, pregnancy conditions, maternal smoking status, and onset of prenatal care; temperature, rain, humidity, air pressure, and windspeed intensity in each trimester of pregnancy; indicators for calendar quarter of gestation; and indicators for prenatal care center. Third trimester values for PM10 and weather variables are averaged across gestation weeks 28 and 36 (or an earlier week if the pregnancy did not reach full term) when the outcome is PTB. In the case of BW or LBW, 3rd trimester averages consider the full length of the trimester until birth. **p<0.01; *p<0.05; # p<0.10.

1. Figure legends

Figure 1: PM10 monthly averages in Montevideo.