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**The Effect of Temporary and Intense Exposure to Particulate Matter on Birth Outcomes in Montevideo**

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**Abstract**

*Background*: Prior estimates of the correlation between ambient air pollutants' concentrations and perinatal health show dispersion in magnitudes, as well as positive and negative signs. These differences may be partially explained by the diverse array of methodological approaches between studies, including the set of confounders considered.

*Objectives*: This study explores the effect of breathable 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: birth weight (BW), the risk of low birth weight (LBW) and the risk of a pre-term birth (PTB).

*Methods*: We exploit the fact that in 2011 the ashes and dust resulting from the eruption of the Puyehue volcano in Chile more than doubled monthly averages of PM10 concentration levels in Montevideo, Uruguay. Using prenatal and birth data for 2010-2013, we estimate the associations between mother's average exposure to PM10 in each trimester-of-pregnancy and perinatal outcomes controlling for a rich set of covariates.

*Results*: We find that exposure to high levels of PM10 concentration (above 50 μg/m³ for the trimester average) during the third trimester of pregnancy is associated with higher rates of low birth weight and prematurity, and lower birth weight. These effects are quite robust to different specifications, and are particularly large for pregnancies exposed to concentration levels above 70 μg/m³, suggesting non-linear effects. The impact of PM10 on BW and on the rate of LBW appears to be driven primarily by an effect on prematurity.

*Conclusions*: Exploiting a natural experiment, our study shows that exposure to high levels of PM10 during the third trimester of pregnancy can trigger preterm births.

## I. Introduction

The Puyehue-Cordon Caulle volcanic complex in Chile experienced a series of eruptions between June and November of 2011. Two days after the first eruption, a cloud of dust arrived in Montevideo. As a result, daily concentrations of particulate matter of up to 10 micrometers (PM10) in Montevideo exceeded the WHO 24-hour mean guideline of 50 µg/m³ (WHO 2006) in 60% of the days in June and July, and were higher than 100 µg/m³ in 30% of the days. A second eruption in November caused a similar increase in PM10 concentration levels in Montevideo. In this paper we exploit this natural phenomenon to analyze the association between exposure to PM10 and birth weight (BW), low birth weight (LBW), and pre-term birth (PTB).

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). LBW has been associated with higher morbidity and lifetime health costs, as well as early mortality (Currie 2009). Moreover, LBW serves as an important mechanism for the intergenerational transmission of economic status (Currie and Madrian 1999; Grossman 2000; Case et al. 2004; Behrman and Rosenzweig 2005; Currie and Moretti 2005; Currie 2009; Figlio et al. 2014).

The empirical evidence on the relationship between ambient air pollutants' concentrations and measures of perinatal health is inconsistent (Dadvand et al. 2013; Parker et al. 2011). (Stieb et al. 2012) review 62 primary studies assessing the effect of ambient concentrations of breathable suspended particles (PM10), fine particles (PM2.5), carbon monoxide (CO), nitrogen dioxide (NO2), sulfur dioxide (SO2), and ozone (O3) on BW, and the risk of LBW and PTB. While slightly more consistent in the case of PM10, the estimates differ substantially in terms of magnitudes and signs. Other reviews of the literature reach similar conclusions (See Currie et al. 2009; Šrám et al. 2005; Woodruff et al. 2009).

This lack of consistency in the literature could either respond to heterogeneity in pollution and population, or may be explained by the diverse array of methodological approaches in the different studies, including differences in the way investigators assess the variation in mothers' exposure to ambient air pollutants, and differences in the set of confounders considered. For example, some studies capture exposure to pollution on a spatio-temporal basis, while others investigate only variation over time. In terms of confounders, few studies consider comprehensive local weather conditions or maternal smoking status, and some fail to control for socioeconomic status or gestational age (Woodruff et al. 2009). These methodological problems have led some authors to question the causality of prior findings (Glinianaia et al. 2004; Maisonet et al. 2004; Stieb et al 2012; Woodruff et al. 2009). In an attempt to address these concerns, (Dadvand et al. 2013) re-estimated previous published articles using a common protocol. Despite some gains in consistency, the variance of the estimates was still high.

Our paper contributes to the literature on outdoor ambient air pollution and perinatal health in several ways. First, we are one of a few studies to analyze the pollution-health-at-birth association by exploiting exogenous variation in pollution resulting from a natural and completely unexpected event that affected the whole city. The use of a natural experiment minimizes concerns about cross-sectional selection. At the same time, it avoids small exposure contrasts, a typical issue in temporal-only approaches. As evidenced in Figure 1, the cloud of ashes that arrived in Montevideo after the eruptions increased sharply the daily concentration levels of PM10 in the city. We are aware of only two other studies exploiting natural experiments to assess the correlation between ambient air pollution and perinatal health. (Parker et al 2005) compare pregnancies exposed to the Utah Valley Steel Mill closure that occurred between mid-1986 and mid-1987 to pregnancies in that region in similar pre-and post-closure calendar periods and not exposed to the mill closure. They find 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) compare pregnancies exposed to the air pollution declines during the 2008 Beijing Olympics to pregnancies pre-and post- Olympic games. Their results show that declines in air pollution late in pregnancy were positively associated with higher birth weight. Reinforcing these prior findings, our results show that pregnancies exposed to higher PM10 levels during the volcano eruption were more likely to end up in premature births and to have lower birth weights. In particular, we find a positive association between exposure to average weekly levels of PM10 above 50 mg during the 7th and 8th month and the likelihood of a premature birth.

Second, our analysis takes into consideration a rich set of mother- and pregnancy-specific characteristics including age, education, marital status, body mass index, parity, week of initiation of prenatal care, maternal smoking status, pregnancy medical conditions (eclampsia and hypertension), and hospital of delivery. In addition, we condition on weather variables and quarter of gestation to account for seasonality (Currie and Schwandt 2013).

Third, most previous studies have been conducted in sites permanently exposed to high levels of air pollution. Our study exploits a transitory and intense increase in ambient pollution in a city with typical low levels of PM10. The distinction may be increasingly important in the years to come if heat waves become more prevalent, as there is strong evidence of a correlation between heat waves and increases in concentrations of PM10 (Katsouyanni and Analitis 2009; Papanastasiou et al. 2013). Furthermore, the health effects of these non-marginal increases in air pollution concentrations during heat waves appear to be substantial (Fischer et al. 2004; Monteiro et al. 2013).

Finally, we provide evidence of the relationship between pollution and birth outcomes in a middle-income country, contributing to expand the evidence for non-developed countries. This is important because underlying health conditions and health services may differ according to the country's level of development, and the effects of pollution may be heterogeneous in these features.

## II. Data

### *Pregnancy and delivery data*

We analyze 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.

Table 1 provides descriptive statistics for the main variables in the analysis by time period (before the Puyehue eruption, during the eruption, and after the eruption). The outcomes of interest are BW, LBW, and PTB. BW is measured in grams. LBW is a binary variable that takes the value of 1 if the BW is 2500 grams or less, and 0 otherwise. We define a PTB as a delivery occurring before the 37$^{th}$ week of gestation. Average BW is increasing throughout the period of analysis and the rates of LBW and prematurity are decreasing. The average rate of LBW in the full period is 7.1% and the average rate of prematurity is 8.1%. For full term births, the average rate of low birth weight is 2.9%.

We consider several maternal characteristics that contribute to address maternal and pregnancy heterogeneity: mother's age, education level (less than middle school, middle school completed, or high school completed), marital status, pregnancy-specific conditions (eclampsia and hypertension), pregnancy risk factors (mother's smoking status, body mass index), parity, onset of prenatal care, and the child's gender. Almost 70% of women belong to the 20-34 age-group, 32% are high school graduates, and 30% have not completed middle school. The majority of mothers (54%) live under common law, 27% are married, and 18%

are single. Almost one out of four women reports smoking during the pregnancy. The majority of women initiate prenatal care during the 12th week of gestation.

Our analysis also accounts for health-care heterogeneity by considering binary indicators for the hospital of delivery. There are 23 maternity hospitals in Montevideo in the period of analysis: 10 are public, covering the poorest fraction of the population (40% of all deliveries) and the rest are 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 drop 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 restrict our sample to pregnancies conceived between 1st June 2009 and April 1st 2013. Overall, our data has 79,332 observations on pregnancies.[1] 26,267 of these pregnancies were exposed to high levels of particulate matter in June, July or November of 2011 due to the ashes from the Puyehue eruption. We observe 24,909 pregnancies with delivery dates prior to the volcano eruption and 28,156 pregnancies with conception dates after the eruption.

### *Air quality data*

The air quality data come 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, SO2, CO, and, NO2) on an hourly basis. This was the only automatic monitoring station in Montevideo operating throughout the full period of analysis (2009-2013).

[1] Our data is a pool of cross-sectional data on pregnancies. We are unable to identify different pregnancies of the same mother.

While three other manual stations in the city collected data of PM10 between 2009 and 2013, we chose not to work with these data because samples in the manual stations are obtained every 6 days and are more likely to miss extreme episodes, such as days with abnormal levels of ashes. In addition, most of the variation in PM10 levels occurs 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.[2] 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 mean level of PM10 during the 1st trimester was 22 µg/m³ for pregnancies not exposed to the Puyehue ashes, and 46 µg/m³ for pregnancies exposed to the ashes (see Table 1). Averages for the first and second trimesters (not shown) were in the same ranges. 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, compared to null exposure to these levels in the periods before and after the ashes.

Our variable of interest is ambient air 24-hour mean concentration of PM10, averaged at the trimester-of-pregnancy level. Specifically, we calculate 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 match each week with the corresponding average PM10 for that week, and then compute the average exposure to PM10 in the first, second, and third trimester-of-pregnancy. Exposure to PM10 during the third trimester depends on the term of gestation. For full-term births (92% of our sample), we compute the third trimester values by averaging PM10 levels between gestation week 28 and gestation week 36. For pre-term births

[2] When PM10 is averaged at the trimester level, the standard deviation of PM10 over time (i.e., within stations) is 14 while the standard deviation between stations is 5.5.

with a delivery before week 36, exposure during the third trimester is computed as the average air quality from gestational week 28 to delivery. Seven percent of all births occur between the 32$^{nd}$ and 36$^{th}$ weeks of gestation and only 1% takes place between gestational weeks 28 and 31.

Table 1 shows also descriptive statistics for other pollutants, including CO2, NO2, and SO2. As in the case of PM10, average levels of CO2 increased during the volcano period and then returned to prior levels. There is no evidence, however, of increases in the levels of NO2 and SO2. Furthermore, we do not find significant correlations between PM10 and other pollutants, except for SO2 in the period prior to the eruptions. Correlation coefficients change signs in the different periods of analysis, suggesting a noisy relationship between the pollutants.

*Weather data and other controls*

We obtain information about temperature, air pressure, winds, humidity, and precipitations 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 average out these measures across all three stations. For each weather variable, we construct trimester-of-pregnancy-specific averages following the same procedure as with PM10.

## III. Statistical analysis

### *Estimation procedure*

We estimate the associations between a pregnant mother's average exposure to PM10 in each trimester of her pregnancy and three perinatal outcomes: birth weight, low birth weight, and prematurity. Our identification strategy relies on the exogenous variation of PM10 concentration over time that resulted from the Puyehue ashes. In the previous section we showed that levels of PM10 in Montevideo, usually under control, increased substantially during that period. The high exposure contrasts in PM10 resulting from this natural experiment justify the use of a temporal identification approach.

The estimation of the association between mother's exposure to PM10 (an aggregate variable with identical values for all women conceiving in the same calendar week) and perinatal outcomes (variables defined at the individual pregnancy level) requres accounting for two types of error correlations: (1) correlation between the errors in pregnancies conceived in the same week (subject to similar shocks), and (2) serial correlation of errors over time. Not accounting for these error correlations can severely affect inference (Moulton 1990, Bertrand, Duflo et al. 2004, Cameron, Gelbach et al. 2008). To address these concerns we followed Loeb and Bound 1996 and Donald and Lang 2007 and run the following two-stage model. The first stage is given by:

$$Y_{i,j,t} = \theta_t + X_i\beta + \mu_j + \varepsilon_{i,j,t} \ , \tag{1}$$

where $Y_{i,j,t}$ is LBW, BW, or PTB for pregnancy $i$ with conception date in week t and at ward j; $\theta_t$ represents a calendar week of conception effect (estimated using 260 dummies for each calendar week of conception in the period); $X_i$ represents a set of maternal/pregnancy individual-level specific characteristics as depicted in Panel A of Table 1 (maternal age, education, marital status, body mass index, smoking status, eclampsia, hypertension, parity, newborn's gender); and $\mu_j$ represents a hospital-of-delivery effect (estimated using 23 hospital-specific dummy variables).

The coefficients on the week-of-conception indicators represent the predicted outcome (low birth weight rate, average birth weight, preterm birth rate) in each calendar week-of-conception for a pregnant woman in the reference category of maternal and pregnancy-specific characteristics. Assuming that the first regression error terms have zero means and are uncorrelated with the observed explanatory variables, in a second stage we fit the following autoregressive model:

$$\hat{\theta}_t = \sum_{j=1}^{3} \alpha_j PM10\_Tj_t + \sum_{j=1}^{3} \gamma_j Wj_t + \sum_{h=1}^{15} \delta_h Q_h + \eta_t \quad , \tag{2}$$

where $\hat{\theta}_t$ is the estimated coefficient obtained in the first stage regression for each of the 260 weeks of conception covered in our sample, $PM10\_Tj_t$ and $Wj_t$ are trimester-of-pregnancy average levels of PM10 and weather data (rain, temperature, atmospheric pressure, humidity, wind), respectively. Third trimester averages are computed between gestation week 28 and gestation week 36. Finally, $Q_t$ are calendar-quarter indicator variables (one dichotomous indicator for each calendar quarter between June 2009 and March 2013). The latter are aimed to capture seasonality in month of conception[3] and other unobserved shocks that could affect the outcomes. This second stage time-series regression avoids problems due to correlation of errors within groups of women conceiving in the same week and allows for serial correlation. After testing for autocorrelation using the Cumby-Huizinga test we proceed to estimate an AR(1) model using a Prais-Winsten regression. We refer to the estimation resulting from equation (2) as the linear-in-means analysis.

In a second specification, for each trimester-of-pregnancy i, we construct three dummy variables indicating exposure to PM10 concentration levels between 30 and 49 μg/m$^3$ (PM30_49_T$_i$), 50 and 69 μg/m$^3$ (PM50_69_T$_i$), and at least 70 μg/m$^3$ (PM70_T$_i$). We refer to the estimations resulting from this specification as the categorized PM10 analysis.

[3] 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.

## IV. Results

### *Linear-in-Means Analysis*

The first stage regressions are presented in Supplemental Material, Table S1. Mothers aged between 20 and 34, those who have completed high school, are married, or have had prior pregnancies, deliver heavier babies and are less likely to have a LBW or a PTB outcome. Pregnancy complications such as eclampsia and hypertension, and risk factors such as being underweight or smoking during pregnancy are associated with lower birth weights and higher PTB and LBW. Obesity is associated with higher birth weight and lower LBW, but increases PTB. Late onset of prenatal care decreases birth weight and increases LBW and PTB.

Table 2 shows the results of the estimation of equation (2) for the case of a linear-in-means specification. Average exposure to PM10 is measured in tens of μg/m$^3$. The first three columns depict the results for BW, LBW and PTB when all births in the sample are considered. The last two columns depict the results of equation (2) only for full-term births. The results show a negative association between average PM10 exposure during the third trimester and birth outcomes. We do not find, however, statistically significant correlations between perinatal outcomes and exposures to PM10 during the first and second trimester. For the third trimester, we find that weight at birth decreases by 10.4 grams per 10 μg/m3 increase in average PM10 concentration during the last trimester of pregnancy, CI: (-16.2, -4.6). A similar increase in PM10 reduces the risks of LBW and PTB by 0.4%, CI: (0.001, 0.007) and 0.4%, CI: (0.001, 0.008) respectively. When we repeat the analysis only for full-term births we do not find statistically significant effects. The latter result suggests that a higher risk of prematurity may be the channel through which PM10 in the third trimester decreases birth weight and increases the risk of low birth weight.

***Categorized PM10 Analysis***

Table 3 shows the results of our categorized PM10 specification. First, we find little evidence of effects of high exposure to PM10 during the first and second trimesters. The only statistically significant effect is a positive association between PM10 concentration levels above 70 ug/m3 in the second trimester and birth weight ($p<0.05$). According to this result, an average PM10 concentration above 70 ug/m3 in the second trimester is associated with a 40 grams increase in birth weight, CI: (1.6, 79.2), compared to pregnancies with PM10 concentrations in the second trimester below 30 ug/m3 (see Column (1)). The result is still observable if we only consider full-term births (Column (4)). We do not find, however, similar effects in the risks of LBW or PTB. We discuss potential explanations for this result in the last section.

Second, as in the linear in means specification, Table 3 shows a negative effect of high levels of PM10 during the third trimester on birth weight. This effect seems to be non-linear, in the sense that it increases with the category of PM10. Average birth weight decreases by 35 grams, CI: (-61.5, -8.8) when PM10 levels are between 50 and 69 and decreases by 49 grams, CI: (-82.8, -14.4) for levels of PM10 above 70. Similar non-linear estimates are observable also in the cases of LBW and prematurity. An average PM10 level between 50 and 69 ug/m3 in the third trimester is associated with a 1.3% increase in the risk of LBW (10% level of significance, CI: (-0.001, 0.026), while an average above 70 ug/m3 is associated with an increase of 2.2%, CI: (0.002-0.042). We observe similar effects in the case of prematurity. As in the linear-in-means analysis, we do not find statistically significant associations between high levels of PM10 and birth weight (or the rate of LBW) for full term births. The effects of 3rd trimester PM10 on the full sample's average birth weight and rate of LBW seem to operate through an increase in the risk of prematurity.

***Sensitivity and Robustness***

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 additional regressions that control for potential confounders.

Supplemental Material, Table S2 depicts 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 are robust to this expanded set of controls, with the estimates for the category PM10>70 slightly larger than those in Table 3.

We next rerun the 2nd stage regression adjusting for the core set of controls plus alternative controls for NO2, SO2, and CO2 averages in each trimester of pregnancy. Results are very similar to those in the core specification when the co-pollutants are NO2 or SO2 (results for the categorical analysis are depicted in Supplemental Material, Table S3 and S4). In the case of CO2, we still observe statistically significant and positive effects of 3rd trimester PM10 on prematurity rates, but the effects are smaller than those in the core specification. The effects on birth weight and low birth weight, on the other hand, lose statistical significance (categorical results are shown in Supplemental Material, Table S5).

A third sensitivity analysis runs both the linear-in-means and categorical models only for observations without missing values on eclampsia, hypertension, parity, and smoking. For each of these variables, the core analysis imputed mean values of the variable to the observations with missing data and added a dichotomous indicator equal to 1 when the observation had a missing value on the variable and 0 otherwise. If women missing observations on these variables are different from other women, and the fraction of these women is changing over time, the estimates could be biased. Table A6 reports the results of this exercise for the categorical model. Very high levels of PM10 (above 70) in the third trimester continue to be strongly associated with birth weight, low birth weight, and prematurity. However, the association with lower levels of PM10 in the 3rd trimester loses statistical significance. Because missing values tend to decrease over time we are more confident about the results that include the full sample of women and impute the missing data.[4] Furthermore, we repeat the analysis without controlling for the variables with missing data in the first stage, and results stay very close to those in the core model.

Fourth, in order to assess the sensitivity to the reference group used for comparison, we restrict our estimation only to pregnancies conceived before or during the volcano eruptions. Supplemental Material, Table S7 shows that results are robust to this change in the sample. In the same way, we rerun the estimation only for pregnancies with a birth date after the first eruption (the sample is restricted to pregnancies exposed to the ashes and pregnancies post-eruption not exposed). Results, shown in Supplemental Material, Table S8, are qualitatively similar, though larger in magnitude, than those in the core analysis.

The use in the same regression of several variables measuring pollution and weather at different points in time raises the challenge of multicollinearity and its potential consequences on the precision of standard errors. In a fifth robustness check, we follow Bell et al (2007) and use residuals of trimester averages regressed on the average of a reference trimester. For example, we select the 1st trimester as the reference trimester and then regress PM10 (and weather) averages for the 2nd and 3rd trimester on the 1st trimester. We rerun the linear-in-means estimation using residuals of the instrumental regressions for the 2nd and 3rd

[4] In the last years, Uruguay implemented a series of pay-per-performance incentives that improved substantially the registry of obstetric records. Women with missing values initially are likely to be different from women with missing records at the end of the period. Removing these women may introduce further bias.

trimesters, as well as the average for the reference category. We repeat this exercise alternating the reference trimester. Results are robust to these variations in the main explanatory variables (see Supplemental Material, Table S9-S11).

Finally, we rerun the birth weight and low birth weight regressions for full term births using, for the 3rd trimester, the PM10 average from gestation week 28 up to the date of delivery (rather than up to gestation week 36). Again we find no effects of PM10 on these outcomes, once gestational age has been accounted for.

## V. Discussion and Conclusions

This paper explores the effect of PM10 on birth weight (BW), low birth weight (LBW) and pre-term birth (PTB). 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 high levels of PM10 concentration during the 3rd trimester are positively associated with LBW and PTB, and reduce BW. The adverse effects of 3rd trimester PM10 are particularly large for pregnancies exposed to concentration levels above 70 µg/m³. They are also quite robust to alternative specifications that control for potentially confounding covariates and use of different samples. We do not find, on the other hand, evidence of PM10 affecting the intrauterine growth rate. Our findings suggest that the effects of PM10 on BW and on the risk of LBW are driven primarily by an effect on prematurity. In particular, our results show that exposures to trimester-of-pregnancy average levels of PM10 above 70 µg/m³ during the third trimester of pregnancy increase the rate of PTB by 4%, with respect to PM10 levels below 30 µg/m³.

We also find, for some specifications, that exposure to average PM10 concentrations above 70 mg during the second trimester is associated with birth weight increases. These findings appear at first sight counterintuitive. One potential explanation is that very high levels of PM10 early in the second trimester (before week 20)[5] may increase the risk of spontaneous abortions. Under this hypothesis, exposure to levels of PM10 above 70 mg during the second trimester 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, Enkhmaa et al. 2014 and Moridi et al. 2014 find strong statistical correlations between ambient air pollutants and spontaneous abortions in Mongolia and Iran, respectively.

We believe this paper contributes to the literature on pollution and health in several ways. First, it is one of a few papers to investigate the association between pollution and perinatal health using a natural experiment. The exogeneity in PM10 variation associated with the volcano eruption, together with the use of a rich set of adjustors (individual-level characteristics, delivery hospital effects, weather measures), provides strong internal validity to the study. Our findings are not subject to the critique that results are being driven by selection of poorer populations into polluted areas and are unlikely to be determined by unobserved time-trends correlated with pollutant trends. Moreover, while in general the findings for this literature are inconsistent, our results are in line with the results in the other two investigations using also natural experiments in Utah and China (Parker et al. 2005 and Rich et al. 2015).

Second, we study transitory and intense exposures to high levels of particulate matter in a city characterized by good air quality. 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. Recent research shows strong evidence of a

[5] Spontaneous abortion refers to the loss of pregnancy before 20 weeks or 500 grams of fetal weight.

correlation between heat waves and an increase in concentrations of PM10. This refinement could be important in a climate change scenario.

Finally, we provide new rigorous evidence of the association between PM10 and perinatal health in a developing country, and in particular in Latin America, where the evidence is scarce.

Our results suggest that exposure to high levels of concentration of PM10 during the third trimester can trigger preterm births. We do not find, on the other hand, evidence of effects on intrauterine growth retardation. Future research should seek to gain insight on the physiological mechanisms behind this effect. Our analysis also identifies specific thresholds above which PM10 can have severe hazardous consequences on pubic health. It contributes, in this way, to the construction of concrete guidelines for public action in the management of air quality. Finally, higher awareness of the consequences of PM10 by clinicians may contribute to palliate some of its adverse effects.

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## VII. Tables

**Table 1: Descriptive statistics, by exposure to Puyehue ashes.**

N (%) for binary variables and mean (± SD) for continuous variables

| | Before eruption (N=24909) *Births conceived between June 2009 and Sept. 2010* | During eruption (N=26267) *Births conceived between Oct. 2010 and Nov. 2011* | After eruption (N=28156) *Births conceived between Dec. 2011 and Mar. 2013* |
|---|---|---|---|
| | (1) | (2) | (3) |
| **Panel A: Individual-level variables** | | | |
| *Pregnancy outcomes* | | | |
| Birth weight (all births) | 3245 (554) | 3283 (540) | 3286 (541) |
| Low birth weight (all births) | 1994 (0.08) | 1745 (0.067) | 1881 (0.067) |
| Premature birth (<37 weeks) | 2191 (0.088) | 2031 (0.078) | 2172 (0.077) |
| Birth weight (only term births) | 3335 (456) | 3361 (451) | 3335 (456) |
| Low birth weight (only term births) | 693 (0.031) | 583 (0.024) | 693 (0.031) |
| *Maternal age* | | | |
| Age <20 | 4098 (0.165) | 4235 (0.162) | 4845 (0.172) |
| 20<=Age<=34 | 17241 (0.692) | 17786 (0.68) | 18932 (0.672) |
| 35<=Age<=39 | 2932 (0.118) | 3387 (0.13) | 3587 (0.127) |
| Age>40 | 638 (0.026) | 733 (0.028) | 792 (0.028) |
| *Maternal education* | | | |
| Less than middle school | 9824 (0.394) | 9647 (0.369) | 10243 (0.364) |
| Middle school <Edu<High school | 7482 (0.3) | 7865 (0.301) | 8453 (0.3) |
| Completed high school | 7603 (0.305) | 8629 (0.33) | 9460 (0.336) |
| *Maternal marital status* | | | |
| Common Law | 13488 (0.541) | 14191 (0.543) | 15712 (0.558) |
| Married | 6751 (0.271) | 7082 (0.271) | 7168 (0.255) |
| Single | 4437 (0.178) | 4647 (0.178) | 5061 (0.18) |
| Other marital status | 233 (0.009) | 221 (0.008) | 215 (0.008) |
| *Pregnancy complications* | | | |
| Eclampsia | 47 (0.002) | 34 (0.001) | 33 (0.001) |
| Eclampsia missing | 3097 (0.124) | 2140 (0.082) | 1405 (0.05) |
| Hypertensio | 572 (0.023) | 556 (0.021) | 661 (0.023) |
| Hypertension missing | 3048 (0.122) | 2114 (0.081) | 1382 (0.049) |
| *Risk factors and other characteristics* | | | |
| Mother underweight | 1598 (0.064) | 1555 (0.059) | 1683 (0.06) |
| Adequate body mass index | 17216 (0.691) | 17799 (0.681) | 18659 (0.663) |
| Mother overweight | 4171 (0.167) | 4543 (0.174) | 5221 (0.185) |
| Mother obese | 1924 (0.077) | 2244 (0.086) | 2593 (0.092) |
| Mother smokes | 6179 (0.248) | 6040 (0.231) | 6411 (0.228) |
| Smoking status missing | 289 (0.012) | 94 (0.004) | 67 (0.002) |
| Parity | 1.147 (1.329) | 1.11 (1.333) | 1.082 (1.279) |
| Parity missing | 3344 (0.134) | 2945 (0.113) | 3470 (0.123) |
| Newborn's gender: male | 12585 (0.505) | 13338 (0.51) | 14432 (0.513) |
| Week of initiation of prenatal care | 12.934 (7.554) | 11.902 (7.095) | 11.401 (6.707) |
| | | | |
| **Panel B: Pollution and weather variables** | | | |
| *Pollution variables* | | | |
| PM10 1st trim (in tens of μg) | 2.044 (0.424) | 4.56 (1.741) | 2.367 (0.865) |
| PM10 < 30 μg | 24547 (0.985) | 5980 (0.229) | 20867 (0.741) |

| | | | |
|---|---|---|---|
| 30 µg≥ PM10 1st trim ≥ 49 µg | 362 (0.015) | 7871 (0.301) | 7289 (0.259) |
| 50 µg ≥ PM10 1st trim ≥ 69 µg | 0 (0) | 9768 (0.374) | 0 (0) |
| PM10 1st trim ≥ 70 µg | 0 (0) | 2522 (0.096) | 0 (0) |
| CO2 1st trimester | 0.485 (0.034) | 1.138 (0.638) | 0.624 (0.118) |
| NO2 1st trimester | 30.091 (9.844) | 24.461 (7.963) | 24.65 (8.584) |
| SO2 1st trimester | 17.933 (6.302) | 11.534 (5.535) | 6.77 (3.225) |
| *Weather variables* | | | |
| Precipitations 1st trimester | 3.68 (0.909) | 2.361 (0.879) | 3.584 (1.068) |
| Temperature 1st trimester | 15.885 (3.962) | 18.094 (4.253) | 17.776 (4.076) |
| Wind 1st trimester | 14.259 (0.84) | 14.599 (1.5) | 13.431 (1.59) |
| Humidity 1st trimester | 74.003 (2.373) | 69.817 (4.041) | 73.506 (4.882) |
| Atmospheric pressure 1st trimester | 1015.87 (2.889) | 1014.942 (2.456) | 1014.892 (2.359) |
| *Correlations between pollutants ++* | | | |
| PM10 and SO2 1st trimester | 0.7376 | -0.3185 | 0.3848 |
| PM10 and NO2 1st trimester | -0.3991 | -0.2058 | -0.2658 |
| PM10 and CO2 1st trimester | -0.3467 | -0.1476 | 0.1256 |

++ Correlation coefficients

**Table 2: Linear-in-means effects of PM10 on birth outcomes (N=200).**

| | All pregnancies | | | Only full term pregnancies | |
|---|---|---|---|---|---|
| | Birthweight | LBW | Prematurity | Birthweight | LBW |
| | (1) | (2) | (3) | (4) | (5) |
| PM10 1st trimester (in tens of µg) | -3.504 | 0.000 | -0.001 | -4.160 | 0.001 |
| | (-10.252,3.244) | (-0.004,0.004) | (-0.005,0.002) | (-10.552,2.231) | (-0.001,0.004) |
| PM10 2nd trimester (in tens of µg) | 5.675 | 0.001 | 0.001 | 5.218 | 0.001 |
| | (-3.860,15.209) | (-0.003,0.005) | (-0.003,0.005) | (-3.261,13.696) | (-0.002,0.004) |
| PM10 3rd trimester (in tens of µg) | -10.379 | 0.004 | 0.004 | -4.541 | -0.000 |
| | (-16.171,-4.587)** | (0.001,0.007)* | (0.001,0.008)** | (-10.101,1.019) | (-0.003,0.002) |

Notes: $2^{nd}$ stage time-series Prais AR(1) regressions. Coefficients and confidence intervals in parentheses. Regression adjusts for weather variables defined at the pregnancy trimester level (rain, temperature, atmospheric pressure, humidity, wind) and for calendar quarter of gestation (one dichotomous indicator for each calendar quarter between June 2009 and March 2013). Both for the PM10 and weather variables, $3^{rd}$ trimester values are measured for the period between gestation week 28 and gestation week 36. **p<0.01; *p<0.05; # p>0.1.

**Table 3: Categorical effects of PM10 on birth outcomes**

| | ---All pregnancies--- | | | --- Only full term pregnancies --- | |
|---|---|---|---|---|---|
| | Birth weight | LBW | Prematurity | Birth weight | LBW |
| | (1) | (2) | (3) | (4) | (5) |
| $30 \geq PM10 \geq 49$ 1st trimester | -8.377 | 0.002 | -0.002 | -10.002 | 0.001 |
| | (-23.131,6.378) | (-0.007,0.011) | (-0.011,0.007) | (-21.773,1.769)# | (-0.005,0.006) |
| $50 \geq PM10 \geq 69$ 1st trimester | 2.256 | -0.002 | -0.006 | -3.409 | -0.000 |
| | (-25.502,30.015) | (-0.016,0.011) | (-0.019,0.007) | (-28.976,22.158) | (-0.009,0.009) |
| $PM10 \geq 70$ 1st trimester | -3.044 | 0.000 | -0.014 | -18.167 | 0.009 |
| | (-50.478,44.390) | (-0.021,0.021) | (-0.034,0.007) | (-62.289,25.955) | (-0.005,0.023) |
| $30 \geq PM10 \geq 49$ 2nd trimester | 0.660 | 0.000 | 0.003 | 6.549 | -0.005 |
| | (-16.533,17.852) | (-0.010,0.010) | (-0.007,0.014) | (-8.298,21.397) | (-0.012,0.003) |
| $50 \geq PM10 \geq 69$ 2nd trimester | 9.546 | 0.009 | 0.007 | 15.727 | 0.003 |
| | (-14.458,33.551) | (-0.004,0.021) | (-0.005,0.019) | (-8.515,39.969) | (-0.007,0.012) |
| $PM10 \geq 70$ 2nd trimester | 40.378 | 0.009 | 0.005 | 48.111 | 0.004 |
| | (1.558,79.197)* | (-0.010,0.028) | (-0.015,0.024) | (11.919,84.303)** | (-0.010,0.018) |
| $30 \geq PM10 \geq 49$ 3rd trimester | -13.325 | -0.003 | 0.008 | -3.882 | -0.010 |
| | (-29.811,3.161) | (-0.012,0.005) | (-0.000,0.016)# | (-19.059,11.295) | (-0.018,-0.001)* |
| $50 \geq PM10 \geq 69$ 3rd trimester | -35.137 | 0.013 | 0.018 | -5.211 | -0.006 |
| | (-61.464,-8.811)** | (-0.001,0.026)# | (0.005,0.031)** | (-27.091,16.670) | (-0.016,0.004) |
| $PM10 \geq 70$ 3rd trimester | -48.596 | 0.022 | 0.025 | -18.371 | 0.000 |
| | (-82.836,-14.356)** | (0.002,0.042)* | (0.005,0.045)* | (-45.885,9.144) | (-0.014,0.014) |

Notes: 2nd stage time-series Prais AR(1) regression. Coefficients and confidence intervals in parentheses. Regression adjusts for weather variables defined at the pregnancy trimester level (rain, temperature, atmospheric pressure, humidity, wind) and for calendar quarter of gestation (one dichotomous indicator for each calendar quarter between June 2009 and March 2013). 3rd trimester averages are computed between gestation week 28 and gestation week 36. **p<0.01; *p<0.05; # p<0.1.

## VIII. Figures

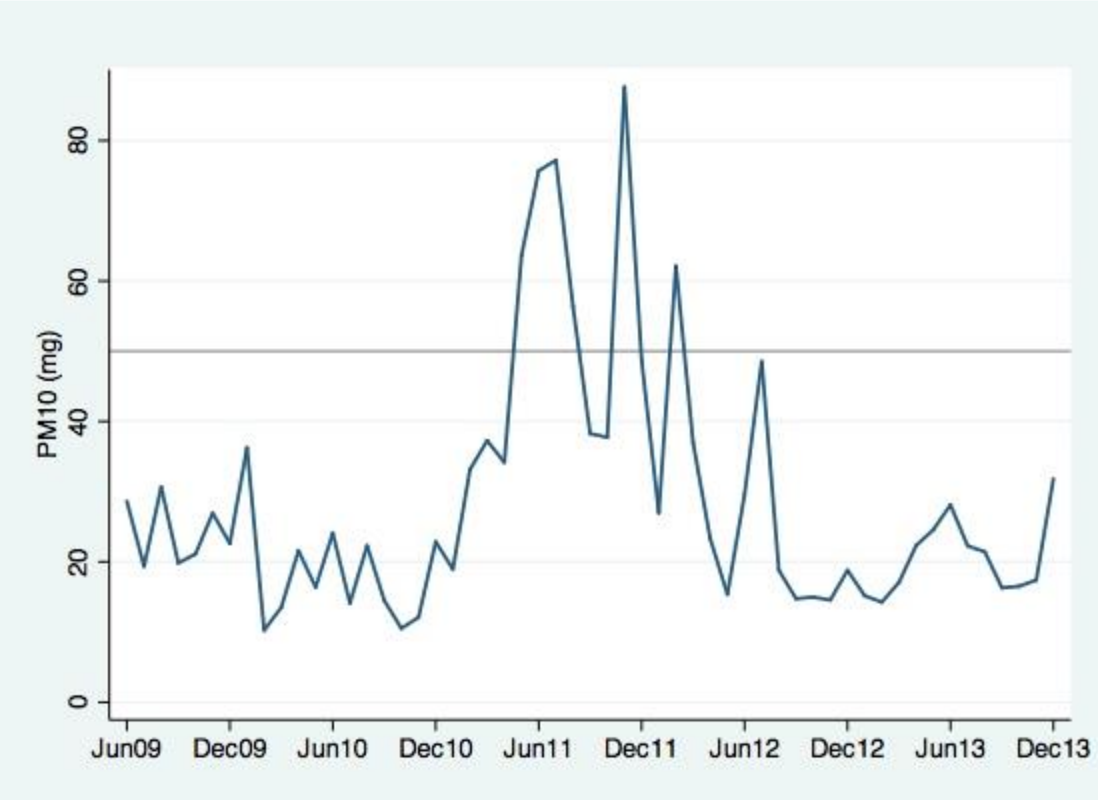


Figure 1: PM10 monthly averages in Montevideo

## IX. Supplemental Material

**Supplemental Material, Table S1: 1st stage individual-level regression.**
Odd ratios (CI) for dichotomous variables, coefficients (CI) for continuous variables.

| | ------------------------------All pregnancies-------------------------------- | | | ----------- Only full term pregnancies --------- | |
|---|---|---|---|---|---|
| | Birth weight | LBW | Prematurity | Birth weight | LBW |
| | (1) | (2) | (3) | (4) | (5) |
| 20<=Age<=34 | 34.00*** | 0.874** | 0.764*** | 13.02* | 1.005* |
| | (22.26,45.74) | (0.807,0.947) | (0.708,0.825) | (3.008,23.02) | (1.001,1.009) |
| 35<=Age<=39 | -21.23* | 1.304*** | 0.997 | -17.69* | 1.015*** |
| | (-38.58,-3.882) | (1.155,1.471) | (0.890,1.116) | (-32.28,-3.106) | (1.009,1.020) |
| Age>40 | -84.87*** | 1.610*** | 1.064 | -77.40*** | 1.032*** |
| | (-113.1,-56.64) | (1.351,1.917) | (0.898,1.261) | (-101.6,-53.16) | (1.021,1.042) |
| Completed high school | 28.67*** | 0.852*** | 0.867** | 16.91** | 0.998 |
| | (16.22,41.12) | (0.776,0.936) | (0.795,0.945) | (6.240,27.59) | (0.994,1.002) |
| Middle school <Edu<High school | 26.27*** | 0.902** | 0.946 | 21.81*** | 0.997 |
| | (16.17,36.37) | (0.839,0.969) | (0.883,1.012) | (13.09,30.53) | (0.994,1.000) |
| Common Law | -0.186 | 1.08 | 1.037 | 4.241 | 1.001 |
| | (-9.969,9.597) | (0.997,1.169) | (0.965,1.114) | (-4.203,12.69) | (0.999,1.004) |
| Single | -23.76*** | 1.195*** | 1.123* | -11.70* | 1.003 |
| | (-37.14,-10.39) | (1.082,1.320) | (1.024,1.231) | (-23.11,-0.294) | (0.999,1.008) |
| Other marital status | 2.408 | 1.015 | 1.087 | 3.982 | 1.004 |
| | (-40.12,44.94) | (0.757,1.360) | (0.832,1.422) | (-33.61,41.58) | (0.989,1.018) |
| Eclampsia | -434.3*** | 4.508*** | 5.099*** | -214.4*** | 1.066 |
| | (-571.2,-297.4) | (2.890,7.033) | (3.437,7.567) | (-322.6,-106.3) | (0.998,1.139) |
| Eclampsia missing | -16.86 | 1.09 | 0.967 | -26.95 | 1.007 |
| | (-104.2,70.48) | (0.656,1.811) | (0.586,1.595) | (-100.3,46.37) | (0.973,1.043) |
| Hypertension | -192.7*** | 2.470*** | 2.395*** | -65.59*** | 1.009 |
| | (-226.3,-159.2) | (2.136,2.856) | (2.097,2.736) | (-91.19,-39.99) | (1.000,1.019) |
| Hypertension missing | 19.47 | 0.823 | 0.989 | 18.97 | 0.992 |
| | (-68.00,106.9) | (0.492,1.375) | (0.596,1.641) | (-54.65,92.60) | (0.958,1.027) |
| Mother’s BMI: underweight | -151.9*** | 1.679*** | 1.350*** | -134.7*** | 1.025*** |
| | (-167.3,-136.6) | (1.528,1.846) | (1.224,1.488) | (-147.8,-121.5) | (1.018,1.032) |
| Mother’s BMI: overweight | 92.65*** | 0.740*** | 0.889** | 87.34*** | 0.990*** |
| | (82.61,102.7) | (0.681,0.804) | (0.826,0.956) | (78.63,96.06) | (0.987,0.993) |
| Mother’s BMI: obese | 132.5*** | 0.845** | 1.143** | 145.6*** | 0.992*** |

| | | | | | |
|---|---|---|---|---|---|
| | (117.6,147.4) | (0.759,0.942) | (1.042,1.252) | (132.8,158.3) | (0.988,0.996) |
| Parity | 25.05*** | 0.940*** | 1.005 | 24.91*** | 0.997*** |
| | (21.40,28.70) | (0.916,0.964) | (0.982,1.029) | (21.83,27.99) | (0.996,0.998) |
| Parity missing | -54.53*** | 1.193** | 1.155** | -44.74*** | 1.006** |
| | (-68.31,-40.76) | (1.073,1.326) | (1.048,1.274) | (-56.63,-32.86) | (1.002,1.010) |
| Mother smokes | -125.5*** | 1.656*** | 1.284*** | -99.99*** | 1.019*** |
| | (-135.2,-115.7) | (1.557,1.762) | (1.208,1.365) | (-108.3,-91.69) | (1.016,1.023) |
| Smoking status missing | -110.5*** | 2.006*** | 1.622** | -54.08* | 1.016 |
| | (-164.1,-56.89) | (1.491,2.698) | (1.206,2.182) | (-95.94,-12.23) | (0.996,1.037) |
| Newborn is male | 113.5*** | 0.842*** | 1.081** | 123.0*** | 0.990*** |
| | (106.1,120.9) | (0.797,0.890) | (1.026,1.138) | (116.6,129.4) | (0.988,0.992) |
| Week of initiation of prenatal care | -2.749*** | 1.012*** | 1.005* | -2.420*** | 1.001*** |
| | (-3.361,-2.138) | (1.008,1.016) | (1.001,1.009) | (-2.955,-1.884) | (1.000,1.001) |

Regression controls for 23 hospital of delivery indicator variables, and for 200 week of gestation indicator variables. **p<0.01; *p<0.05; # p<0.1

**Supplemental Material, Table S2: 2nd stage categorical analysis controlling for activity in thermal power plants and oil refinery**

| | -------------------------------All pregnancies-------------------------------- | | | ----------- Only full term pregnancies --------- | |
|---|---|---|---|---|---|
| | Birthweight | LBW | Prematurity | Birthweight | LBW |
| | (1) | (2) | (3) | (4) | (5) |
| 30 ≥ PM10 ≥ 49 1st trimester | -5.669 | 0.003 | -0.002 | 0.002 | -12.941 |
| | (-25.087,13.749) | (-0.008,0.013) | (-0.012,0.009) | (-0.006,0.011) | (-29.003,3.121) |
| 50 ≥ PM10 ≥ 69 1st trimester | -1.073 | -0.001 | 0.003 | -0.003 | -3.556 |
| | (-31.753,29.608) | (-0.016,0.015) | (-0.014,0.020) | (-0.014,0.008) | (-31.735,24.623) |
| PM10 ≥ 70 1st trimester | 1.441 | -0.001 | -0.000 | -0.004 | 0.860 |
| | (-53.979,56.860) | (-0.028,0.027) | (-0.032,0.031) | (-0.024,0.015) | (-52.364,54.083) |
| 30 ≥ PM10 ≥ 49 2nd trimester | 4.855 | -0.001 | 0.002 | -0.006 | 8.799 |
| | (-13.143,22.853) | (-0.012,0.011) | (-0.010,0.014) | (-0.015,0.003) | (-6.282,23.881) |
| 50 ≥ PM10 ≥ 69 2nd trimester | 16.412 | 0.005 | 0.011 | -0.008 | 32.125 |
| | (-8.576,41.400) | (-0.011,0.021) | (-0.005,0.027) | (-0.020,0.005) | (4.236,60.015)* |
| PM10 ≥ 70 2nd trimester | 39.618 | 0.010 | 0.019 | -0.008 | 67.788 |
| | (3.415,75.822)* | (-0.011,0.032) | (-0.006,0.044) | (-0.026,0.010) | (31.577,103.999)** |
| 30 ≥ PM10 ≥ 49 3rd trimester | -13.846 | -0.006 | 0.008 | -0.013 | 0.268 |
| | (-31.635,3.943) | (-0.016,0.005) | (-0.002,0.017) | (-0.022,-0.004)** | (-15.781,16.316) |
| 50 ≥ PM10 ≥ 69 3rd trimester | -34.153 | 0.014 | 0.023 | -0.008 | 6.404 |
| | (-62.112,-6.195)* | (-0.001,0.030)# | (0.009,0.037)** | (-0.020,0.004) | (-17.164,29.973) |
| PM10 ≥ 70 3rd trimester | -60.904 | 0.030 | 0.037 | -0.000 | -11.282 |
| | (-102.642,-19.166)** | (0.007,0.054)* | (0.012,0.061)** | (-0.017,0.017) | (-46.573,24.010) |

Notes: 2nd stage time-series Prais AR(1) regression. Coefficients and confidence intervals in parentheses. Regression adjusts for weather variables defined at the pregnancy trimester level (rain, temperature, atmospheric pressure, humidity, wind), activity at two thermal power stations and one oil refinery, and for calendar quarter of gestation (one dichotomous indicator for each calendar quarter between June 2009 and March 2013). 3rd trimester averages are computed between gestation week 28 and gestation week 36. **p<0.01; *p<0.05; # p<0.1.

**Supplemental Material, Table S3: 2nd stage categorical analysis controlling for SO2**

| | ---All pregnancies--- | | | --- Only full term pregnancies --- | |
|---|---|---|---|---|---|
| | Birthweight | LBW | Prematurity | Birthweight | LBW |
| | (1) | (2) | (3) | (4) | (5) |
| 30 ≥ PM10 ≥ 49 1st trimester | -4.217 | 0.001 | -0.001 | -5.529 | -0.002 |
| | (-19.899,11.465) | (-0.009,0.010) | (-0.011,0.009) | (-18.098,7.041) | (-0.008,0.004) |
| 50 ≥ PM10 ≥ 69 1st trimester | 5.981 | -0.003 | -0.001 | 1.183 | -0.003 |
| | (-23.316,35.277) | (-0.017,0.012) | (-0.016,0.014) | (-24.999,27.365) | (-0.012,0.006) |
| PM10 ≥ 70 1st trimester | 3.952 | -0.002 | -0.008 | -10.615 | 0.004 |
| | (-44.888,52.792) | (-0.024,0.020) | (-0.031,0.015) | (-54.534,33.305) | (-0.010,0.018) |
| 30 ≥ PM10 ≥ 49 2nd trimester | 2.007 | -0.001 | 0.004 | 7.762 | -0.006 |
| | (-14.868,18.883) | (-0.011,0.010) | (-0.007,0.015) | (-6.583,22.107) | (-0.013,0.002) |
| 50 ≥ PM10 ≥ 69 2nd trimester | 16.106 | 0.006 | 0.008 | 22.461 | -0.001 |
| | (-9.186,41.398) | (-0.007,0.019) | (-0.005,0.022) | (-2.097,47.019)# | (-0.011,0.009) |
| PM10 ≥ 70 2nd trimester | 46.997 | 0.006 | 0.007 | 55.198 | -0.000 |
| | (7.894,86.100)* | (-0.013,0.025) | (-0.014,0.027) | (20.495,89.902)** | (-0.014,0.014) |
| 30 ≥ PM10 ≥ 49 3rd trimester | -14.222 | -0.003 | 0.008 | -4.398 | -0.009 |
| | (-30.727,2.284)# | (-0.011,0.006) | (0.000,0.016)* | (-19.067,10.272) | (-0.018,-0.001)* |
| 50 ≥ PM10 ≥ 69 3rd trimester | -32.153 | 0.012 | 0.019 | -0.083 | -0.008 |
| | (-59.750,-4.556)* | (-0.003,0.027) | (0.004,0.033)* | (-21.294,21.129) | (-0.018,0.002) |
| PM10 ≥ 70 3rd trimester | -28.662 | 0.014 | 0.028 | 4.238 | -0.011 |
| | (-68.245,10.920) | (-0.010,0.037) | (0.005,0.050)* | (-28.776,37.253) | (-0.029,0.007) |

Notes: 2nd stage time-series Prais AR(1) regression. Coefficients and confidence intervals in parentheses. Regression adjusts for weather variables defined at the pregnancy trimester level (rain, temperature, atmospheric pressure, humidity, wind), average exposure to SO2 in each trimester of pregnancy, and calendar quarter of gestation (one dichotomous indicator for each calendar quarter between June 2009 and March 2013). For weather and pollution variables 3rd trimester measures are computed between gestation week 28 and gestation week 36. **p<0.01; *p<0.045; # p>0.1.

## Supplemental Material, Table S4: 2nd stage categorical analysis controlling for NO2

| | --------------------------------All pregnancies | --------------------------------- | | ----------- Only full term pregnancies --------- | |
|---|---|---|---|---|---|
| | Birthweight | LBW | Prematurity | Birthweight | LBW |
| | (1) | (2) | (3) | (4) | (5) |
| 30 ≥ PM10 ≥ 49 1st trimester | -7.840 | 0.002 | -0.003 | -9.801 | 0.001 |
| | (-22.885,7.205) | (-0.007,0.012) | (-0.012,0.006) | (-21.885,2.283) | (-0.005,0.007) |
| 50 ≥ PM10 ≥ 69 1st trimester | 3.236 | -0.003 | -0.004 | -0.130 | -0.002 |
| | (-25.323,31.794) | (-0.017,0.011) | (-0.017,0.009) | (-25.529,25.269) | (-0.011,0.007) |
| PM10 ≥ 70 1st trimester | 3.344 | -0.002 | -0.013 | -10.098 | 0.006 |
| | (-45.910,52.598) | (-0.024,0.019) | (-0.035,0.009) | (-54.938,34.743) | (-0.007,0.020) |
| 30 ≥ PM10 ≥ 49 2nd trimester | 3.522 | -0.001 | 0.003 | 9.182 | -0.005 |
| | (-13.224,20.268) | (-0.011,0.009) | (-0.008,0.014) | (-5.328,23.691) | (-0.013,0.002) |
| 50 ≥ PM10 ≥ 69 2nd trimester | 13.421 | 0.007 | 0.006 | 18.247 | 0.002 |
| | (-10.709,37.552) | (-0.005,0.020) | (-0.006,0.018) | (-6.299,42.794) | (-0.008,0.011) |
| PM10 ≥ 70 2nd trimester | 46.784 | 0.007 | 0.004 | 55.462 | 0.002 |
| | (6.352,87.215)* | (-0.013,0.026) | (-0.016,0.024) | (19.661,91.264)** | (-0.012,0.016) |
| 30 ≥ PM10 ≥ 49 3rd trimester | -13.695 | -0.003 | 0.006 | -5.900 | -0.008 |
| | (-30.172,2.781) | (-0.012,0.006) | (-0.002,0.014) | (-21.073,9.273) | (-0.016,0.000)# |
| 50 ≥ PM10 ≥ 69 3rd trimester | -35.709 | 0.014 | 0.015 | -8.798 | -0.003 |
| | (-62.608,-8.810)** | (0.000,0.028)* | (0.002,0.029)* | (-30.929,13.333) | (-0.013,0.006) |
| PM10 ≥ 70 3rd trimester | -54.488 | 0.025 | 0.021 | -31.371 | 0.005 |
| | (-92.113,-16.863)** | (0.004,0.047)* | (0.000,0.042)* | (-62.022,-0.721)* | (-0.009,0.020) |

Notes: 2nd stage time-series Prais AR(1) regression. Coefficients and confidence intervals in parentheses. Regression adjusts for weather variables defined at the pregnancy trimester level (rain, temperature, atmospheric pressure, humidity, wind), average exposure to NO2 in each trimester of pregnancy, and calendar quarter of gestation (one dichotomous indicator for each calendar quarter between June 2009 and March 2013). 3rd trimester averages are computed between gestation week 28 and gestation week 36. **p<0.01; *p<0.045; # p>0.1.

**Supplemental Material, Table S5: 2nd stage categorical analysis, controlling for CO2**

| | --------------------------------All pregnancies--------------------------------- | | | ----------- Only full term pregnancies --------- | |
|---|---|---|---|---|---|
| | Birthweight | LBW | Prematurity | Birthweight | LBW |
| | (1) | (2) | (3) | (4) | (5) |
| 30 ≥ PM10 ≥ 49 1st trimester | -3.695 | -0.000 | -0.005 | -8.257 | -0.000 |
| | (-19.210,11.820) | (-0.010,0.009) | (-0.014,0.005) | (-20.895,4.381) | (-0.006,0.005) |
| 50 ≥ PM10 ≥ 69 1st trimester | 15.145 | -0.007 | -0.010 | 3.785 | -0.003 |
| | (-14.737,45.027) | (-0.022,0.008) | (-0.025,0.005) | (-22.093,29.662) | (-0.012,0.007) |
| PM10 ≥ 70 1st trimester | 30.140 | -0.011 | -0.024 | 0.329 | 0.004 |
| | (-23.164,83.444) | (-0.036,0.014) | (-0.049,0.002)# | (-45.497,46.156) | (-0.013,0.021) |
| 30 ≥ PM10 ≥ 49 2nd trimester | -3.993 | 0.002 | 0.006 | 5.403 | -0.005 |
| | (-21.400,13.413) | (-0.009,0.013) | (-0.006,0.018) | (-9.209,20.014) | (-0.013,0.004) |
| 50 ≥ PM10 ≥ 69 2nd trimester | 19.846 | 0.008 | 0.006 | 23.872 | 0.001 |
| | (-5.366,45.058) | (-0.006,0.021) | (-0.006,0.019) | (-1.076,48.821)# | (-0.009,0.012) |
| PM10 ≥ 70 2nd trimester | 47.395 | 0.013 | 0.010 | 57.920 | 0.004 |
| | (10.118,84.672)* | (-0.005,0.031) | (-0.008,0.027) | (22.624,93.217)** | (-0.011,0.019) |
| 30 ≥ PM10 ≥ 49 3rd trimester | -14.893 | -0.003 | 0.010 | -3.323 | -0.010 |
| | (-32.586,2.800)# | (-0.013,0.008) | (0.001,0.018)* | (-18.926,12.280) | (-0.020,-0.001)* |
| 50 ≥ PM10 ≥ 69 3rd trimester | -18.531 | 0.014 | 0.019 | 8.017 | -0.006 |
| | (-49.200,12.137) | (-0.003,0.031) | (0.003,0.035)* | (-17.233,33.267) | (-0.017,0.005) |
| PM10 ≥ 70 3rd trimester | 21.094 | 0.005 | 0.006 | 20.650 | -0.006 |
| | (-56.817,99.004) | (-0.033,0.044) | (-0.028,0.041) | (-47.616,88.917) | (-0.033,0.021) |

Notes: 2nd stage time-series Prais AR(1) regression. Coefficients and confidence intervals in parentheses. Regression adjusts for weather variables defined at the pregnancy trimester level (rain, temperature, atmospheric pressure, humidity, wind), trimester of pregnancy exposure to CO2, and calendar quarter of gestation (one dichotomous indicator for each calendar quarter between June 2009 and March 2013). 3rd trimester weather and pollution measures are computed between gestation week 28 and gestation week 36. **p<0.01; *p<0.05; # p<0.1.

**Supplemental Material, Table S6: Excluding observations with missing values on eclampsia, hypertension, parity, and smoking**

| | ---All pregnancies--- | | | --- Only full term pregnancies --- | |
|---|---|---|---|---|---|
| | Birthweight | LBW | Prematurity | Birthweight | LBW |
| | (1) | (2) | (3) | (4) | (5) |
| 30 ≥ PM10 ≥ 49 1st trimester | -4.192 | -0.000 | -0.006 | -8.841 | 0.002 |
| | (-22.368,13.984) | (-0.011,0.010) | (-0.016,0.005) | (-21.998,4.317) | (-0.004,0.007) |
| 50 ≥ PM10 ≥ 69 1st trimester | 5.308 | -0.010 | -0.016 | -10.748 | 0.001 |
| | (-26.655,37.272) | (-0.026,0.006) | (-0.033,0.001)# | (-38.287,16.791) | (-0.009,0.010) |
| PM10 ≥ 70 1st trimester | 5.002 | -0.012 | -0.033 | -32.262 | 0.011 |
| | (-48.745,58.748) | (-0.038,0.014) | (-0.061,-0.004)* | (-77.366,12.842) | (-0.005,0.027) |
| 30 ≥ PM10 ≥ 49 2nd trimester | -1.336 | -0.002 | -0.001 | 0.885 | -0.005 |
| | (-22.260,19.588) | (-0.014,0.011) | (-0.012,0.011) | (-16.526,18.295) | (-0.014,0.004) |
| 50 ≥ PM10 ≥ 69 2nd trimester | 5.281 | 0.011 | 0.003 | 8.524 | 0.006 |
| | (-24.435,34.997) | (-0.005,0.027) | (-0.011,0.018) | (-20.157,37.206) | (-0.005,0.016) |
| PM10 ≥ 70 2nd trimester | 53.752 | 0.003 | -0.003 | 52.645 | 0.003 |
| | (0.050,107.454)* | (-0.020,0.027) | (-0.029,0.022) | (7.814,97.476)* | (-0.013,0.019) |
| 30 ≥ PM10 ≥ 49 3rd trimester | -16.866 | -0.006 | 0.001 | -12.936 | -0.009 |
| | (-37.554,3.821) | (-0.018,0.005) | (-0.008,0.011) | (-31.031,5.159) | (-0.018,0.000)# |
| 50 ≥ PM10 ≥ 69 3rd trimester | -29.721 | 0.007 | 0.011 | -5.752 | -0.009 |
| | (-61.697,2.255)# | (-0.010,0.024) | (-0.005,0.027) | (-30.227,18.724) | (-0.020,0.003) |
| PM10 ≥ 70 3rd trimester | -60.187 | 0.032 | 0.037 | -11.439 | -0.003 |
| | (-101.700,-18.673)** | (0.004,0.059)* | (0.010,0.064)** | (-48.076,25.199) | (-0.019,0.013) |

Notes: $2^{nd}$ stage time-series Prais AR(1) regression. Coefficients and confidence intervals in parentheses. Regression adjusts for weather variables defined at the pregnancy trimester level (rain, temperature, atmospheric pressure, humidity, wind) and for calendar quarter of gestation (one dichotomous indicator for each calendar quarter between June 2009 and March 2013). $3^{rd}$ trimester averages are computed between gestation week 28 and gestation week 36. **p<0.01; *p<0.05; # p<0.1.

**Supplemental Material, Table S7: Only pregnancies conceived before or during the volcano eruptions**

| | --------------------------------All pregnancies--------------------------------- | | | ----------- Only full term pregnancies --------- | |
|---|---|---|---|---|---|
| | Birthweight | LBW | Prematurity | Birthweight | LBW |
| | (1) | (2) | (3) | (4) | (5) |
| 30 ≥ PM10 ≥ 49 1st trimester | 20.273 | -0.004 | -0.009 | -0.799 | 0.006 |
| | (-21.987,62.534) | (-0.019,0.010) | (-0.033,0.015) | (-28.526,26.928) | (-0.009,0.021) |
| 50 ≥ PM10 ≥ 69 1st trimester | 29.584 | -0.009 | -0.012 | 7.041 | 0.004 |
| | (-18.993,78.160) | (-0.027,0.009) | (-0.039,0.015) | (-28.093,42.175) | (-0.012,0.021) |
| PM10 ≥ 70 1st trimester | 30.854 | -0.017 | -0.026 | -7.447 | 0.009 |
| | (-34.865,96.574) | (-0.042,0.008) | (-0.060,0.008) | (-63.293,48.398) | (-0.012,0.030) |
| 30 ≥ PM10 ≥ 49 2nd trimester | -3.352 | -0.002 | 0.007 | 3.586 | -0.009 |
| | (-29.148,22.444) | (-0.018,0.014) | (-0.009,0.023) | (-16.608,23.779) | (-0.020,0.003) |
| 50 ≥ PM10 ≥ 69 2nd trimester | 9.435 | 0.005 | 0.009 | 15.424 | -0.001 |
| | (-18.348,37.217) | (-0.011,0.022) | (-0.007,0.025) | (-11.953,42.801) | (-0.014,0.012) |
| PM10 ≥ 70 2nd trimester | 30.527 | 0.015 | 0.012 | 49.662 | 0.004 |
| | (-4.961,66.016)# | (-0.004,0.034) | (-0.009,0.034) | (15.235,84.090)** | (-0.013,0.020) |
| 30 ≥ PM10 ≥ 49 3rd trimester | -21.407 | -0.002 | 0.012 | -5.674 | -0.012 |
| | (-41.995,-0.819)* | (-0.013,0.008) | (0.002,0.022)* | (-24.455,13.107) | (-0.023,-0.002)* |
| 50 ≥ PM10 ≥ 69 3rd trimester | -43.163 | 0.019 | 0.023 | -6.976 | -0.004 |
| | (-71.981,-14.346)** | (0.004,0.034)* | (0.010,0.037)** | (-33.096,19.144) | (-0.018,0.009) |
| PM10 ≥ 70 3rd trimester | -54.623 | 0.034 | 0.029 | -22.670 | 0.008 |
| | (-95.423,-13.823)** | (0.010,0.058)** | (0.006,0.052)* | (-56.628,11.288) | (-0.010,0.026) |

Notes: $2^{nd}$ stage time-series Prais AR(1) regression. Coefficients and confidence intervals in parentheses. Regression adjusts for weather variables defined at the pregnancy trimester level (rain, temperature, atmospheric pressure, humidity, wind) and for calendar quarter of gestation (one dichotomous indicator for each calendar quarter between June 2009 and March 2013). $3^{rd}$ trimester averages are computed between gestation week 28 and gestation week 36. **p<0.01; *p<0.05; # p<0.1.

**Supplemental Material, Table S8: Only pregnancies conceived during or after the volcano eruptions**

| | --------------------------------All pregnancies--------------------------------- | | | ----------- Only full term pregnancies --------- | |
|---|---|---|---|---|---|
| | Birthweight | LBW | Prematurity | Birthweight | LBW |
| | (1) | (2) | (3) | (4) | (5) |
| 30 ≥ PM10 ≥ 49 1st trimester | -5.931 | 0.004 | -0.001 | -7.365 | -0.000 |
| | (-23.256,11.394) | (-0.006,0.014) | (-0.011,0.009) | (-23.487,8.757) | (-0.007,0.006) |
| 50 ≥ PM10 ≥ 69 1st trimester | 4.103 | 0.002 | -0.004 | -2.486 | -0.001 |
| | (-28.159,36.364) | (-0.015,0.019) | (-0.020,0.013) | (-32.453,27.480) | (-0.012,0.010) |
| PM10 ≥ 70 1st trimester | 2.942 | 0.001 | -0.012 | -14.776 | 0.003 |
| | (-49.249,55.133) | (-0.025,0.026) | (-0.038,0.014) | (-64.421,34.870) | (-0.014,0.020) |
| 30 ≥ PM10 ≥ 49 2nd trimester | 3.414 | 0.002 | 0.009 | 10.342 | -0.003 |
| | (-14.210,21.038) | (-0.011,0.015) | (-0.006,0.023) | (-7.527,28.212) | (-0.012,0.005) |
| 50 ≥ PM10 ≥ 69 2nd trimester | 26.217 | 0.004 | 0.006 | 26.257 | -0.001 |
| | (1.634,50.801)* | (-0.011,0.020) | (-0.011,0.023) | (-0.702,53.215)# | (-0.012,0.011) |
| PM10 ≥ 70 2nd trimester | 51.576 | 0.007 | 0.007 | 54.658 | 0.003 |
| | (14.497,88.655)** | (-0.013,0.027) | (-0.016,0.029) | (16.613,92.703)** | (-0.013,0.019) |
| 30 ≥ PM10 ≥ 49 3rd trimester | -9.214 | -0.001 | 0.006 | -4.604 | -0.003 |
| | (-25.915,7.487) | (-0.013,0.010) | (-0.008,0.019) | (-22.220,13.012) | (-0.012,0.007) |
| 50 ≥ PM10 ≥ 69 3rd trimester | -33.692 | 0.015 | 0.017 | -6.274 | 0.002 |
| | (-59.509,-7.874)* | (0.000,0.030)* | (-0.001,0.035)# | (-29.882,17.335) | (-0.008,0.012) |
| PM10 ≥ 70 3rd trimester | -88.615 | 0.049 | 0.057 | -17.311 | 0.008 |
| | (-127.746,-49.484)** | (0.023,0.074)** | (0.025,0.089)** | (-51.731,17.110) | (-0.010,0.027) |

Notes: $2^{nd}$ stage time-series Prais AR(1) regression. Coefficients and confidence intervals in parentheses. Regression adjusts for weather variables defined at the pregnancy trimester level (rain, temperature, atmospheric pressure, humidity, wind) and for calendar quarter of gestation (one dichotomous indicator for each calendar quarter between June 2009 and March 2013). $3^{rd}$ trimester averages are computed between gestation week 28 and gestation week 36. **p<0.01; *p<0.05; # p<0.1.

**Supplemental Material, Table S9: Substituting 1st and 3rd trimester pollution and weather values for residuals of these measures on 2nd trimester values**

| | All pregnancies | | | Only full term pregnancies | |
|---|---|---|---|---|---|
| | Birthweight | LBW | Prematurity | Birthweight | LBW |
| | (1) | (2) | (3) | (4) | (5) |
| PM10 1st trimester (in tens of µg) | -0.849 | 0.001 | -0.001 | -1.719 | 0.001 |
| | (-9.509,7.811) | (-0.004,0.005) | (-0.005,0.003) | (-9.759,6.322) | (-0.002,0.005) |
| PM10 2nd trimester (in tens of µg) | 5.675 | 0.001 | 0.001 | 5.218 | 0.001 |
| | (-3.860,15.209) | (-0.003,0.005) | (-0.003,0.005) | (-3.261,13.696) | (-0.002,0.004) |
| PM10 3rd trimester (in tens of µg) | -7.874 | 0.004 | 0.005 | -2.238 | -0.000 |
| | (-14.958,-0.790)* | (0.001,0.007)* | (0.001,0.008)** | (-9.760,5.284) | (-0.003,0.003) |

Notes: $2^{nd}$ stage time-series Prais AR(1) regressions. Coefficients and confidence intervals in parentheses. Regression adjusts for weather variables defined at the pregnancy trimester level (rain, temperature, atmospheric pressure, humidity, wind) and for calendar quarter of gestation (one dichotomous indicator for each calendar quarter between June 2009 and March 2013). PM10 and weather variables in the $3^{rd}$ trimester values are measured for the period between gestation week 28 and gestation week 36. **p<0.01; *p<0.05; # p<0.1.

**Supplemental Material, Table S10: Substituting 2nd and 3rd trimester pollution and weather values for residuals of these measures on 1st trimester values**

| | All pregnancies | | | Only full term pregnancies | |
|---|---|---|---|---|---|
| | Birthweight | LBW | Prematurity | Birthweight | LBW |
| | (1) | (2) | (3) | (4) | (5) |
| PM10 1st trimester (in tens of µg) | -3.504 | 0.000 | -0.001 | -4.160 | 0.001 |
| | (-10.252,3.244) | (-0.004,0.004) | (-0.005,0.002) | (-10.552,2.231) | (-0.001,0.004) |
| PM10 2nd trimester (in tens of µg) | 3.109 | 0.001 | -0.000 | 2.172 | 0.001 |
| | (-8.305,14.522) | (-0.004,0.006) | (-0.005,0.004) | (-8.143,12.486) | (-0.002,0.005) |
| PM10 3rd trimester (in tens of µg) | -10.004 | 0.004 | 0.005 | -4.095 | -0.001 |
| | (-15.824,-4.184)** | (0.001,0.007)* | (0.001,0.008)** | (-9.760,1.569) | (-0.003,0.002) |

Notes: $2^{nd}$ stage time-series Prais AR(1) regressions. Coefficients and confidence intervals in parentheses. Regression adjusts for weather variables defined at the pregnancy trimester level (rain, temperature, atmospheric pressure, humidity, wind) and for calendar quarter of gestation (one dichotomous indicator for each calendar quarter between June 2009 and March 2013). Both for the PM10 and weather variables, $3^{rd}$ trimester values are measured for the period between gestation week 28 and gestation week 36. **p<0.01; *p<0.05; # p<0.1.

**Supplemental Material, Table S11: Substituting 2nd and 3rd trimester pollution and weather values for residuals of these measures on 1st trimester values**

| | All pregnancies | | | Only full term pregnancies | |
|---|---|---|---|---|---|
| | Birthweight | LBW | Prematurity | Birthweight | LBW |
| | (1) | (2) | (3) | (4) | (5) |
| PM10 1st trimester (in tens of µg) | -2.263 | -0.000 | -0.002 | 0.001 | -3.617 |
| | (-9.030,4.504) | (-0.004,0.004) | (-0.006,0.002) | (-0.001,0.004) | (-10.104,2.869) |
| PM10 2nd trimester (in tens of µg) | -2.323 | 0.004 | 0.004 | 0.000 | 1.718 |
| | (-12.760,8.114) | (-0.001,0.009) | (-0.000,0.008)# | (-0.003,0.004) | (-8.797,12.234) |
| PM10 3rd trimester (in tens of µg) | -10.379 | 0.004 | 0.004 | -0.000 | -4.541 |
| | (-16.171,-4.587)** | (0.001,0.007)* | (0.001,0.008)** | (-0.003,0.002) | (-10.101,1.019) |

Notes: 2$^{nd}$ stage time-series Prais AR(1) regressions. Coefficients and confidence intervals in parentheses. Regression adjusts for weather variables defined at the pregnancy trimester level (rain, temperature, atmospheric pressure, humidity, wind) and for calendar quarter of gestation (one dichotomous indicator for each calendar quarter between June 2009 and March 2013). Both for the PM10 and weather variables, 3$^{rd}$ trimester values are measured for the period between gestation week 28 and gestation week 36. **p<0.01; *p<0.05; # p<0.1.