

Prenatal Exposure to Ambient Air Pollution, Gestational Weight Gain, and Offspring Birth
Weight

Zengjing Liu

A thesis

submitted in partial fulfillment of the
requirements for the degree of

Master of Public Health

University of Washington

2020

Committee:

Daniel Enquobahrie

Adam Szpiro

Program Authorized to Offer Degree:

Epidemiology

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Zengjing Liu

University of Washington

Abstract

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Zengjing Liu

Chair of the Supervisory Committee:

Daniel Enquobahrie

Department of Epidemiology

Background: Insufficient or excessive gestational weight gain (GWG) impacts the progression and outcomes of pregnancy with consequences on mothers and their offspring over the life course. Environmental factors, such as ambient air pollution, have been associated with weight change in animal models and non-pregnant populations. However, association of ambient air pollution with GWG and subsequent birth outcomes is not well investigated. We investigated associations of particulate matter with a diameter of less than 2.5 micrometers (PM_{2.5}) with GWG and infant birth weight.

Methods: The present study was conducted among a subset of participants from the Omega Study, a prospective pregnancy cohort. Exposure to PM_{2.5} was predicted for participants based on their residential address using a national spatiotemporal model. Separate multivariable linear regression models, adjusted for relevant confounders, were used to estimate associations of trimester-specific and monthly (corresponding to months in pregnancy) PM_{2.5} exposures with early (<20 weeks gestation), late (≥20 weeks gestation), and total GWG, as well as associations of trimester-specific and monthly PM_{2.5} exposures with infant birth weight. To examine whether

pre-pregnancy BMI (ppBMI) and infant sex modified the associations, stratified models and interaction terms were used.

Results: Average age of the participants was 32.87 years, and average PM_{2.5} exposure during the first, second, and third trimester were 5.10 µg/m³, 20.23 µg/m³, and 14.68 µg/m³, respectively. There was no evidence of an overall association between trimester-specific and monthly PM_{2.5} exposure and early, late, or total GWG. However, higher third trimester PM_{2.5} exposure was associated with higher late (0.40 kg per 5 µg/m³ PM_{2.5} exposure; 95% CI: 0.12, 0.67) and total (0.35 kg per 5 µg/m³ PM_{2.5} exposure; 95% CI: 0.01, 0.70) GWG among participants with normal ppBMI. Similar associations were not observed among the overweight/obese group for third trimester PM_{2.5} exposure and late (0.09 kg; 95% CI: -0.32, 0.49) and total (-0.06 kg; 95%CI: -0.57, 0.46) GWG (p-value for interaction > 0.05). Higher second month PM_{2.5} exposure was associated with lower early (-0.70 kg; 95% CI: -1.22, -0.18), late (-0.84 kg; 95% CI: -1.54, -0.14), and total (-1.70 kg; 95% CI: -2.57, -0.82) GWG among participants with overweight/obese ppBMI. However, among participants with normal ppBMI, there was no evidence of an association between second month PM_{2.5} exposure and early (0.10 kg; 95% CI: -0.28, 0.48), late (-0.16 kg; 95% CI: -0.67, 0.35), and total (-0.01 kg; 95% CI: -0.66, 0.64) GWG. Terms for interaction were significant for second month PM_{2.5} exposure and early and total GWG (p-values = 0.01 and p-value < 0.01, respectively). Higher third trimester PM_{2.5} exposure was associated with higher birth weight (102.75 g per 5 µg/m³ PM_{2.5} exposure; 95% CI: 70.65, 134.85), though higher fourth month PM_{2.5} exposure was associated with lower birth weight (-66.34 g per 5 µg/m³ PM_{2.5} exposure; 95% CI: -126.61, -6.08). Interactions of PM_{2.5} with ppBMI or infant sex on birth weight were not statistically significant.

Conclusions: Associations of PM_{2.5} with GWG vary by exposure window and ppBMI while associations of PM_{2.5} with birth weight potentially vary by exposure window. Future studies that

examine these associations among diverse populations and studies that evaluate underlying biological mechanisms are needed.

Introduction

Insufficient or excessive gestational weight gain (GWG) have been associated with several adverse maternal and neonatal pregnancy outcomes. Infants of women with inadequate GWG are at higher risks for low birth weight, preterm births, and small for gestational age.¹⁻⁴ Excessive GWG has been associated with pregnancy complications (gestational diabetes, gestational hypertension, and preeclampsia) and poor infant birth outcomes (higher risks of fetal macrosomia and large for gestational age).^{4,5} These adverse pregnancy outcomes can impact women and their offspring over the life course, such as a predisposition to chronic cardiovascular, respiratory, and metabolic diseases.⁶ Based on the 2009 Institute of Medicine (IOM) recommendations of GWG for pregnant women, only 31% of women giving birth to full-term, singleton infants in 2015 had GWG within the recommended range, with 48% gaining more weight than recommended and 21% gaining less weight.⁷

Besides dietary patterns^{8,9}, physical activity levels¹⁰, and socioeconomic status^{11,12}, environmental factors, such as ambient air pollution, may play key roles in GWG. Studies in the general non-pregnant population have suggested links between exposure to ambient air pollution and body weight, with higher air pollution exposure associated with higher BMI.¹³⁻¹⁵ Furthermore, animal studies have shown that pregnant rats exposed to unfiltered Beijing air, measured by concentrations of atmospheric particulate matter with a diameter of less than 2.5 micrometers (PM_{2.5}), had higher mean body weight at the end of their pregnancies compared to those exposed to filtered air.¹⁶ Ambient air pollution has also been associated with pregnancy complications (e.g. preeclampsia) and adverse birth outcomes, specifically preterm birth, low birth weight, and small for gestational age, all of which have also been linked to abnormal GWG.¹⁷⁻²⁵ However, most studies that examined ambient air pollution and weight gain were conducted in animal models and non-pregnant populations.¹³⁻¹⁶

To our knowledge, only one study examined the association between ambient air pollution and GWG and found higher trimester-specific GWG associated with higher PM_{2.5} exposure in

the respective trimesters.²⁶ Observations of associations between air pollution with both higher GWG, which has been linked to higher birth weight²⁷, and low birth weight^{17–19} indicate potential complex relationships between air pollution, GWG, and birth weight. These relationships may also be modified by pre-pregnancy BMI (ppBMI) and infant sex. Higher ppBMI has been associated with GWG above IOM recommendations²⁸ as well as fetal macrosomia.²⁹ Previous research has also shown sex-specific differences in response to changes in the intrauterine environment and maternal characteristics.^{30,31} However, research is sparse on effect modifying roles of ppBMI and infant sex in the context of air pollution, GWG, and birth weight, and reported evidence is conflicting.^{32–34}

Air pollution represents one of the major environmental risk factors to health in modern day³⁵ and affects nearly all parts of society, regardless of age, sex, race, ethnicity, or socioeconomic status. As air pollution continues to rise, a better understanding of its impacts on health outcomes, particularly among vulnerable populations such as pregnant women, can have potential research, practice, and policy implications. The proposed study aimed to understand the relationships between ambient air pollution, GWG, and birth weight, while considering effect modification by ppBMI and infant sex. Findings can be used to inform further research efforts targeted to improve maternal and child health outcomes in the context of ambient air pollution exposure.

Methods

Study Design and Setting

This was a prospective cohort study, with PM2.5 as the primary exposure and GWG and offspring birth weight as outcomes. Study subjects were selected among participants of the Omega Study, a prospective pregnancy cohort. During 1996 to 2008, pregnant women receiving prenatal care at clinics affiliated with Swedish Medical Center and Tacoma General Hospital in Washington State were recruited to be part of the Omega Study and followed through delivery.

Women were eligible to participate if they were at least 18 years old, able to read and speak English, initiated prenatal care before 20 weeks gestation, planned to carry pregnancy to term, and delivered at one of the two study hospitals. Approximately 79% of the eligible women approached had consented to participate, and 97% completed study follow-up. Study participants provided written informed consent, and the Institutional Review Boards at Swedish Medical Center and Tacoma General Hospital approved the study.

Study Participants

The proposed study was conducted among 1,000 Omega Study participants for whom PM2.5 exposure was predicted (see participant characteristics below). Participants in this subset who had singleton pregnancies, complete data on GWG and birth weight, and date of last menstrual period (LMP) on or after December 1, 1998 (PM2.5 predictions started December 1998) were included in the analyses, for a final sample of 855 out of the 1,000 participants (for whom PM2.5 was predicted). Characteristics of this sub-cohort were, in general, similar to characteristics of participants from the parent cohort – the Omega Study (Table 1).

Data Collection

Maternal characteristics including information on sociodemographic characteristics, residential addresses, reproductive and medical histories, and behaviors before pregnancy were collected by trained interviewers shortly after enrollment (16 weeks gestation on average). Participants were followed until delivery, and study personnel abstracted maternal and infant medical records to ascertain course and outcomes of pregnancy.

PM2.5 Assessment

PM2.5 exposure was defined as the amount of atmospheric particulate matter with a diameter of less than 2.5 micrometers that participants were predicted to be exposed to (in $\mu\text{g}/\text{m}^3$)

over the course of their pregnancies, averaged into four-week periods. Trimester-specific PM2.5 exposure was estimated based on self-reported date of LMP or early ultrasound estimate. The sum of monthly particulate predictions that corresponded with conception to 12 weeks were first trimester PM2.5 exposure, 13 to 27 weeks were the second trimester, and 28 weeks to delivery were the third trimester. Monthly PM2.5 exposure estimates corresponding to the months in pregnancy were also assessed for each participant.

A national spatiotemporal model predicting ambient PM2.5 exposure specific to the Pacific Northwest region was developed based on two sources, Environmental Protection (EPA) Agency Air Quality System (AQS) measurements and a series of monitoring campaigns including measurements from the Multi-Ethnic Study of Atherosclerosis and Air Pollution (MESA Air) and the New York City Community Air Survey (NYCCAS). Monitoring campaigns collected two-week time-integrated averages of PM2.5 measurements, and the EPA AQS PM2.5 measurements were averaged to match these two-week periods. In each modeling region, first, common temporal trends from the time-series of long-term two-week measurements were estimated, then relative contributions of each temporal trend were estimated as a function of geographic covariates and space (e.g. distance to roadway, distance to greenery, length of roadway). Predictions were made by residential address at the time of participant enrollment, according to which modeling region that location falls within. Locations in multiple modeling regions were averaged, resulting in a smooth prediction surface. Due to differing two-week monitor schedules used between the modeling regions, measurements were scaled down to one-week periods. These one-week schedules were averaged to a consistent four-week schedule used for this study. Past national spatiotemporal PM2.5 models have explained on average 89% of spatial variability and 64% of temporal variability.³⁶

Gestational Weight Gain Assessment

GWG was defined as the amount of weight (in kg) participants gained throughout their pregnancies. Early and late GWG were calculated based on self-reported date of LMP or early ultrasound estimate and maternal weight. Early GWG was calculated as the difference between weight at 20 weeks gestation and pre-pregnancy weight. Late GWG was calculated as the difference between the last weight before delivery and weight at 20 weeks gestation. Overall GWG was calculated as the difference in weight between the last recorded maternal weight prior to delivery and self-reported pre-pregnancy weight prior to conception. Excessive, adequate, and inadequate GWG categories were calculated based on IOM guidelines.³⁷ Early GWG rate were calculated as early GWG divided by 20 weeks. Late GWG rate were calculated as late GWG divided by the difference between gestational age at delivery and 20 weeks. Overall GWG rate were calculated as total GWG divided by gestational age at delivery.

Birth Weight Assessment

Infant birth weight was defined as the weight of a baby (in g) at birth. Measurements were recorded immediately after birth and available in medical records.

Covariate Assessment

ppBMI was calculated based on the pre-pregnancy weight and self-reported height. Using standard weight status categories³⁸, four levels of ppBMI were created, <18.5 kg/m², 18.5-24.9 kg/m², 25.0-29.9 kg/m², and ≥30.0 kg/m² for underweight, normal, overweight, and obese, respectively. Due to lower numbers in the latter two categories, ppBMI was dichotomized, with one category being the normal weight group and the other category being the combination of overweight and obese groups. Infant sex (male and female) was assessed based on abstracted medical records. Other key covariates included maternal age (continuous variable in years), race (categorical variable; “non-Hispanic White”, “African American”, “Asian”, and “Other”), maternal education (binary variable; “high school education or more” and “less than high school

education”), parity (binary variable; “nulliparous” and “multiparous”), smoking status (binary variable; “ever smoker” and “never smoker”), calendar year of conception (continuous variable based on LMP or early ultrasound estimate), and season of conception (categorical variable; “Fall”, “Winter”, “Spring”, and “Summer” based on LMP or early ultrasound estimate).

Data Analysis

We examined the distributions of PM_{2.5} predictions and maternal and infant characteristics by calculating mean and standard deviation for continuous variables and frequency and percentage for categorical variables. Characteristics of these participants were compared to the general Omega Study participants to demonstrate similarity. The distributions were also assessed for normality and outliers. Multivariate linear regression models were used to assess GWG for every 5 µg/m³ higher PM_{2.5} exposure, with PM_{2.5} as the independent variable and GWG as the dependent variable. Separate models were used for trimester-specific and monthly PM_{2.5} exposures as well as early, late, and total GWG. Models characterizing trimester-specific PM_{2.5} exposures were primary models. Similarly, we used linear regression models to examine associations of PM_{2.5} exposure (every 5 µg/m³ higher) with infant birth weight. PM_{2.5} was the independent variable and birth weight was the dependent variable. Separate models were again used for trimester-specific and monthly PM_{2.5} exposure, with those characterizing trimester-specific PM_{2.5} as the primary models. All models were adjusted for maternal age, race, education, parity, smoking status, calendar year of conception, and season of conception.

To examine whether ppBMI modified the associations of PM_{2.5} and GWG as well as PM_{2.5} and infant birth weight, analyses were repeated with stratification by the two BMI groups – normal weight and overweight/obese. Stratified analyses by infant sex (male/female) were also conducted to assess for effect modification of the associations of PM_{2.5} with birth weight. Statistical significance of multiplicative interactions was assessed using interaction terms included in the models.

In sensitivity analyses, we repeated the analyses for full-term births only. Additionally, to estimate the odds of excess GWG (according to IOM guidelines) associated with higher PM2.5 exposure, multivariable adjusted logistic regression models were used. Rate of GWG was also evaluated through multivariable logistic regression to estimate the odds of higher (>1 standard deviation above the mean) early, late, and overall GWG rate.

All analyses were conducted using Stata 16.0 (College Station, TX) and R version 3.6.0 (R Foundation for Statistical Computing, Vienna, Austria). Two-sided α of 0.05 was used.

Results

The average age of the participants was 32.87 years and average GWG during the entire pregnancy was 13.20 kg. Average PM2.5 exposure during the first, second, and third trimesters were 5.10 $\mu\text{g}/\text{m}^3$, 20.23 $\mu\text{g}/\text{m}^3$, and 14.68 $\mu\text{g}/\text{m}^3$, respectively. A majority of the participants were in the normal ppBMI category (66.55%), nulliparous (56.02%), non-Hispanic White (85.26%), non-smokers (74.40%), had post high school education (97.62%), and had adequate GWG according to IOM guidelines (41.68%). The average infant birth weight was 3,436.28 g, and 50.85% of infants were male.

In overall adjusted models, there was no evidence of associations of trimester-specific and monthly PM2.5 exposure with early, late, or total GWG (Table 2). However, in ppBMI stratified models, higher third trimester PM2.5 exposure was associated with both higher late (0.40 kg per 5 $\mu\text{g}/\text{m}^3$ PM2.5 exposure; 95% CI: 0.12, 0.67) and total (0.35 kg per 5 $\mu\text{g}/\text{m}^3$ PM2.5 exposure; 95% CI: 0.01, 0.70) GWG among participants with normal ppBMI (Tables 3-4; Figures 1-2). Similar associations were not observed among the overweight/obese group for third trimester PM2.5 exposure and late (0.09 kg; 95% CI: -0.32, 0.49) or total (-0.06 kg; 95% CI: -0.57, 0.46) GWG. Terms for interaction by ppBMI, however, were not significant for late or total GWG (p -values = 0.19 and 0.18, respectively). On the other hand, we observed that higher second month PM2.5 exposure was associated with lower early (-0.70 kg; 95% CI: -1.22, -0.18), late (-0.84 kg;

95% CI: -1.54, -0.14), and total (-1.70 kg; 95% CI: -2.57, -0.82) GWG among participants with overweight/obese ppBMI (Tables 5-6; Figures 3-4). Among participants with normal ppBMI, there was no evidence of an association between second month PM2.5 exposure and early (0.10 kg; 95% CI: -0.28, 0.48), late (-0.16 kg; 95% CI: -0.67, 0.35), and total (-0.01 kg; 95% CI: -0.66, 0.64) GWG. Terms for interaction were significant for only early and total GWG (p-values = 0.01 and p-value < 0.01, respectively).

Higher third trimester PM2.5 exposure was associated with higher birth weight (102.75 g per 5 $\mu\text{g}/\text{m}^3$ PM2.5 exposure; 95% CI: 70.65, 134.85), while higher fourth month PM2.5 exposure was associated with lower birth weight (-66.34 g per 5 $\mu\text{g}/\text{m}^3$ PM2.5 exposure; 95% CI: -126.61, -6.08) (Table 7). These associations for trimester-specific PM2.5 exposure were similar among groups defined by ppBMI or infant sex (Tables 8-11; Figures 5-8) (all interaction p-values > 0.05). Higher fourth month PM2.5 exposure and lower birth weight associations were observed among participants with normal ppBMI (-76.67 g; 95% CI: -148.63, -4.70) and male infants (-113.76 g; 95% CI: -190.40, -37.12), but not among women with overweight/obese ppBMI (-78.16 g; 95% CI: -170.37, 14.05) or female infants (-13.59 g; 95% CI: -94.46, 67.29). Interaction terms by ppBMI and infant sex, however, were not significant (all interaction p-values > 0.05).

Sensitivity analyses among full-term births yielded similar findings to those reported above, though the magnitude of the associations were slightly attenuated for participants with only full-term births (Tables 12-21; Figures 9-16). Analyses assessing odds of excess GWG (based on IOM classification) or GWG rate with higher PM2.5 exposure did not find any associations (Table 22-25).

Discussion

In the current study, we found that higher third trimester PM2.5 exposure was associated with higher late and total GWG among women with normal weight ppBMI. On the other hand, we found that higher second month PM2.5 exposure was associated with lower early, late, and total

GWG among women with overweight/obese ppBMI. While the multiplicative interactions by ppBMI were not statistically significant for third trimester PM2.5, they were significant for second month PM2.5 exposure and early and total GWG. Higher third trimester PM2.5 exposure was associated with higher birth weight, while higher fourth month PM2.5 exposure was associated with lower infant birth weight, relationships that were still seen after stratifying by ppBMI and infant sex.

Only one study to date have examined the association between air pollution and GWG. Liao *et al* analyzed associations of PM2.5 exposure with GWG during the first, second, and third trimesters among a birth cohort of women from Wuhan City, China.²⁶ Researchers found that higher PM2.5 exposure in each trimester was associated with higher GWG in the respective trimester. 10 $\mu\text{g}/\text{m}^3$ higher PM2.5 exposure during the first, second, and third trimesters were associated with 0.15 kg, 0.15 kg, and 0.13 kg higher GWG during the first, second and third trimesters, respectively. These findings were similar to our observations only for normal weight ppBMI women during the third trimester, though the magnitude of the associations differed. This could be due to differences in the study populations, baseline PM2.5 exposure, and categorization of GWG. Higher percentage of the participants in the previous study were in the underweight ppBMI group (19.12% vs 4.69% in our study) while a lower percentage were in the overweight/obese ppBMI group (13.16% vs 28.75% in our study). Additionally, there were lower levels of participants reporting inadequate GWG according to IOM guidelines (9.56% vs 22.31% in our study) and higher levels of participants reporting excessive GWG (54.81% vs 36.01% in our study) in the study by Liao *et al*. The researchers also reported up to eight times higher PM2.5 concentration for each trimester to what we observed in our study. Median PM2.5 concentrations were 117.30 $\mu\text{g}/\text{m}^3$ (vs 13.55 $\mu\text{g}/\text{m}^3$), 81.50 $\mu\text{g}/\text{m}^3$ (vs 18.35 $\mu\text{g}/\text{m}^3$), and 72.10 $\mu\text{g}/\text{m}^3$ (vs 13.52 $\mu\text{g}/\text{m}^3$) for first, second, and third trimester, respectively. With regards to analytic approach, Liao *et al* categorized GWG differently and only assessed changes to trimester-specific GWG. Therefore, it is unknown if similar associations would have been observed had they assessed for early, late, and total GWG. Furthermore, the study did not evaluate effect modification by ppBMI,

so we are unsure if results of the previous study would differ across women of different ppBMI. Liao and colleagues also did not examine monthly exposures of PM_{2.5} in relation to GWG, and we could not compare our findings related to monthly PM_{2.5} exposure.

Other studies have assessed associations between ambient air pollution and weight gain in the non-pregnant population with mixed results. There have been indications that children exposed to higher pollutant concentrations have higher odds of being overweight or obese, as evidenced in Barcelona, Spain.¹³ Additionally, research on young adults in southern California found that higher air pollution exposure was associated with higher liver fat, which has been strongly linked to obesity.³⁹ However, the same study did not find significant associations between ambient air pollution exposure and BMI levels. Similarly, a study investigating the relationship between ambient air pollution and weight gain in a cohort of African-American women in the US found no association.⁴⁰ The mixed results were further illustrated in a systematic review that found 44% of the reviewed studies observed higher air pollution exposure associated with higher body weight, 12% observed associations with lower body weight, and 44% did not observe any associations.⁴¹ Since pregnancy involves a different physiological state, associations found in non-pregnant populations may not be generalizable to those who are pregnant, thereby highlighting the need for further studies among the pregnant population. Furthermore, different measures of pollutant concentrations were used for different studies (e.g. nitrogen dioxide, ozone), thus further contributing to the inconsistency of findings.

More studies have been conducted assessing the relationship between PM_{2.5} and infant birth weight. In Guangdong, China, higher levels of PM_{2.5} exposure during the first and last months of pregnancy were associated with higher odds of low birth weight.⁴² The odds of low birth weight among participants exposed to 10 µg/m³ higher PM_{2.5} during the first and last months of pregnancy were 1.06 and 1.08 times higher, respectively. These associations were in agreement to our observation of 66.34 g lower birth weight for every 5 µg/m³ higher PM_{2.5} exposure during the fourth month of pregnancy. It's important to note, however, that our study used birth weight

as a continuous variable, whereas the previous study dichotomized birth weight into two categories (low birth weight and not low birth weight). Studies conducted in Rhode Island⁴³, Brisbane, Australia⁴⁴, and Ningbo, China²² also found that higher PM_{2.5} exposure during each trimester and/or over the entire pregnancy was associated with lower birth weight. Research on mother-infant pairs at Rhode Island found that for every 2.50 µg/m³ higher PM_{2.5} exposure over the entire pregnancy, birth weight was lower by 15.90 g. However, there was no association observed with regards to trimester-specific PM_{2.5} exposure and changes in birth weight. Similarly, research from Brisbane, Australia found that for every 1.30 µg/m³ higher PM_{2.5} exposure over the whole pregnancy, the risk of low birth weight was 1.06 times higher, while no associations were observed with trimester-specific PM_{2.5} exposure. Finally, in Ningbo, China, for every 10.55 µg/m³ higher PM_{2.5} exposure during the first, second, and third trimester, birth weight was lower by approximately 10 g, 8 g, and 5 g, respectively. These findings contrasted with results we have observed. In our study, we found that higher PM_{2.5} exposure during the third trimester was associated with higher birth weight (102.75 g per 5 µg/m³ PM_{2.5} exposure) while we found no association between first and second trimester PM_{2.5} exposure and infant birth weight.

Our results examining effect modification by ppBMI also contradicted with past research. From a study conducted in Los Angeles, researchers found that among women with similar PM_{2.5} exposures, those in the higher ppBMI categories had higher risk of low infant birth weight compared to mothers with normal ppBMI.³⁴ Although there was no association between air pollution and birth weight for participants with normal weight or overweight ppBMI, for participants in the highest ppBMI quintile (> 35 kg/m²), the odds of low birth weight was 1.24 times higher in the group exposed to 5.82 µg/m³ higher PM_{2.5} exposure throughout the course of the pregnancy. In contrast, our study found higher third trimester PM_{2.5} exposure associated with higher birth weight for both normal ppBMI (107.25 g) and overweight/obese ppBMI participants (90.69 g), while lower birth weight was observed with higher PM_{2.5} exposure during the fourth month of pregnancy only among participants with normal ppBMI (-76.67 g).

When we stratified by infant sex, our results were similar to findings from previous research. Fong *et al* assessed the association between PM_{2.5} and birth weight. They found that for every 2.3 µg/m³ higher PM_{2.5} exposure throughout the pregnancy, birth weight was on average 16 g lower, but no evidence of effect modification by infant sex was found.³³ In a separate study conducted by Jedrychowski *et al*, no significant interaction between PM_{2.5} exposure and infant sex were found, but stratified analysis showed that a 30 µg/m³ higher PM_{2.5} exposure during pregnancy was associated with a 189 g lower birth weight in male infants compared to 17 g lower birth weight in female infants.³² Similarly, although our study also found no evidence of statistically significant multiplicative interaction by infant sex (all interaction p-values > 0.05), there was evidence of lower birth weight associated with PM_{2.5} exposure during the fourth month of pregnancy, specifically among male infants (-113.76 g).

Several mechanisms have been posited for the adverse effects of air pollution on maternal and fetal health. Short- and long-term exposure to air pollution particulates, such as PM_{2.5}, have been associated with higher systemic inflammation, even among healthy, non-smoking adults^{45,46}, and inflammation during pregnancy has been associated with higher rates of GWG.⁴⁷ Another possible explanation for higher GWG associated with higher PM_{2.5} exposure is due to the impact of ambient air pollution on physical activity. Exercising during pregnancy has been associated with lowering the risk of excessive GWG and promoting appropriate birth weight^{48,49}, but existing research has suggested that ambient air pollution discouraged physical activity, especially among those with respiratory disease.⁵⁰ It is possible that those exposed to higher air pollution particulates are less likely to be physically active, thereby resulting in higher GWG. Additionally, for the present study, we observed differential exposure effects on GWG among participants in the normal ppBMI group (positive associations) compared to those in the overweight/obese ppBMI group (inverse associations). It is possible that for the latter group, nutritional and physical activity interventions affected the relationships that were observed.

Inhaling air pollution particulates during gestation may also affect fetal growth. Exposure to ambient air pollution particulates can result in placental dysfunction through induction of inflammatory responses, disruption to the endocrine systems, and mitochondrial interference.^{51,52} This can impair healthy development of the fetus and contribute to the lower birth weight observed in previous studies and in the present study (with monthly PM2.5 exposure). However, we instead observed higher birth weight associated with third trimester PM2.5 exposure. Studies have shown that women with higher GWG have a higher risk of having infants with macrosomia and infants who are large for gestational age.^{53,54} This contrasts with the potential birth weight lowering effect of PM2.5 reported in other previous studies, but may account for seemingly conflicting findings in the current analyses. A post-hoc analysis assessing GWG as a mediator in the association between PM2.5 and infant birth weight was not significant. This highlights the potential importance of other underlying factors influencing weight gain and infant birth weight.

This study had several strengths that deserve mention. The prediction models used to characterize PM2.5 exposure were developed based on multiple sources of particulate measurements. These models provided a finer window of assessment, thereby allowing us to assess associations based on trimester-specific and monthly PM2.5 exposure. Additionally, we used a large cohort of well-characterized pregnant women on whom detailed data were available, which provided us the opportunity to assess GWG during different time periods throughout the pregnancy. However, there were several limitations in our study that merit discussion. Air pollution models only captured information based on participants' residence at time of enrollment and were not updated if participants moved nor did it record daily outdoor activities or occupational exposure. Therefore, misclassification of PM2.5 is possible if participants moved since enrollment into the Omega Study or they did not spend most of their time at home. The models also averaged PM2.5 exposure over monthly intervals based on differing two-week monitoring schedules. Misclassification may also have been introduced because the monthly air pollution intervals did not line up with participants' exact pregnancy dates. Additionally, some amount of temporal

measurement error is possible due to the inconsistent monitoring schedules between the EPA AQS measurements and cohort-specific monitoring campaign measurements. Furthermore, self-reported measures of pre-pregnancy body weight were used, and underestimation of pre-pregnancy weight is likely among women of greater ppBMI. Lastly, this study draws its study population from the Omega Study, of which participants are mostly non-Hispanic White individuals of high socioeconomic status. Potential issues with generalizability of findings are possible if there are underlying mechanisms that results in differing associations among racially/ethnically diverse or lower socioeconomic status populations.

In summary, we found that maternal third trimester PM_{2.5} exposure was associated with higher GWG among pregnant women with normal ppBMI while second month PM_{2.5} exposure was associated with lower GWG among women with overweight/obese ppBMI. Third trimester PM_{2.5} exposure was associated with higher birth weight, while fourth month PM_{2.5} exposure was associated with lower infant birth weight. Our findings add further evidence supporting complex relationships between PM_{2.5}, GWG, and birth weight, though further studies among diverse populations and studies that evaluate underlying biological mechanisms are needed. Findings from these studies can guide recommendations and screening approaches among vulnerable populations to improve maternal and child health outcomes.

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Tables and Figures

Table 1. Characteristics of air pollution study participants compared with general Omega Study participants*

Characteristics	Air Pollution Study Participants (N = 855)**	General Omega Study Participants (N = 3,772)**
	Mean (Standard Deviation)	Mean (Standard Deviation)
Maternal age (years)	32.87 (4.38)	32.82 (4.53)
Gestational weight gain (kg)		
Early***	4.13 (2.63)	4.24 (2.64)
Late***	9.28 (3.66)	9.08 (4.04)
Overall	13.20 (4.87)	13.10 (4.97)
PM2.5 (µg/m³)		
First Trimester	15.10 (5.65)	
Second Trimester	20.23 (7.26)	
Third Trimester	14.68 (6.16)	
Fetal Birth Weight (g)	3,436.28 (557.36)	3,452 (548.37)
	N (%)	N (%)
Pre-Pregnancy Body Mass Index (kg/m²)		
<18.5 (Underweight)	40 (4.69)	163 (4.33)
18.5 – 24.9 (Normal weight)	567 (66.55)	2,587 (68.79)
25.0 – 29.9 (Overweight)	166 (19.49)	665 (17.68)
≥30 (Obese)	79 (9.27)	346 (9.20)
Season of conception		
Winter	195 (22.81)	905 (23.99)
Spring	227 (26.55)	957 (25.37)
Summer	222 (25.96)	971 (25.75)
Fall	211 (24.68)	939 (24.89)
Nulliparous	479 (56.02)	2,170 (57.54)
Race		
Non-Hispanic White	729 (85.26)	3,197 (84.76)
African American	13 (1.52)	66 (1.75)
Asian	66 (7.72)	298 (7.90)
Other	47 (5.50)	211 (5.59)
Ever smoker	204 (25.60)	929 (26.85)

High school education or less	19 (2.38)	122 (3.51)
Infant Sex		
Male	419 (50.85)	1,865 (51.65)
Female	405 (49.15)	1,746 (48.35)
Institute of Medicine Gestational Weight Gain Categories		
Inadequate	189 (22.31)	888 (23.84)
Adequate	353 (41.68)	1,529 (41.06)
Excessive	305 (36.01)	1,307 (35.10)

*Included only singleton pregnancies and participants whose last menstrual period date was December 1998 or later (PM2.5 predictions started December 1998); Characteristics were not significantly different

**Numbers may not add up due to missing data

***Early gestational weight gain is the difference between weight at 20 weeks gestation and pre-pregnancy weight; Late gestational weight gain is the difference between last weight before delivery and weight at 20 weeks

Table 2. Associations between trimester-specific and monthly PM2.5 exposure (every 5 µg/m³ higher) with early, late, and total gestational weight gain (kg)*

PM2.5 Exposure by Trimester	Gestational Weight Gain		
	Early** Kg (95% CI)	Late** Kg (95% CI)	Total Kg (95% CI)
Trimester 1	N = 766 0.100 (-0.112, 0.312)	N = 764 0.039 (-0.248, 0.325)	N = 774 0.080 (-0.286, 0.446)
Trimester 2		N = 764 -0.045 (-0.259, 0.169)	N = 774 -0.131 (-0.403, 0.141)
Trimester 3		N = 753 0.228 (-0.007, 0.463)	N = 761 0.132 (-0.165, 0.429)
PM2.5 Exposure by Months in Pregnancy			
Month 1	N = 766 0.160 (-0.148, 0.468)	N = 764 0.020 (-0.395, 0.434)	N = 774 0.164 (-0.362, 0.691)
Month 2	N = 766 -0.176 (-0.496, 0.143)	N = 764 -0.309 (-0.739, 0.122)	N = 774 -0.522 (-1.072, 0.028)
Month 3	N = 766 -0.114 (-0.443, 0.214)	N = 764 -0.077 (-0.521, 0.366)	N = 774 -0.279 (-0.841, 0.282)
Month 4	N = 766 -0.093 (-0.388, 0.203)	N = 764 -0.130 (-0.527, 0.268)	N = 774 -0.317 (-0.821, 0.188)
Month 5	N = 766 -0.081 (-0.382, 0.221)	N = 764 -0.170 (-0.576, 0.236)	N = 774 -0.289 (-0.807, 0.229)
Month 6		N = 762 0.085 (-0.382, 0.51)	N = 770 -0.301 (-0.888, 0.286)
Month 7		N = 762 -0.143 (-0.559, 0.274)	N = 770 -0.308 (-0.839, 0.223)
Month 8		N = 757 -0.161 (-0.587, 0.265)	N = 765 -0.230 (-0.772, 0.313)
Month 9		N = 640 0.275 (-0.201, 0.751)	N = 647 0.104 (-0.500, 0.707)

*Adjusted for maternal age, race, maternal education, parity, smoking status, calendar year, and season
 **Early gestational weight gain is the difference between weight at 20 weeks gestation and pre-pregnancy weight; Late gestational weight gain is the difference between last weight before delivery and weight at 20 weeks

Table 3. Association of trimester-specific PM2.5 exposure (every 5 µg/m³ higher) with early, late, and total gestational weight gain (kg) stratified by pre-pregnancy body mass index*

	Pre-Pregnancy Body Mass Index (kg/m ²)		
	Normal Weight (18.5 – 24.9)	Overweight (25.0 – 29.9)	Obese (≥30)
Early Gestational Weight Gain (kg, 95% CI)**			
PM2.5 Exposure			
Trimester 1	N = 513	N = 147	N = 67
	0.173 (-0.063, 0.410)	0.155 (-0.336, 0.646)	
Trimester 2			
Trimester 3			
Late Gestational Weight Gain (kg, 95% CI)**			
PM2.5 Exposure			
Trimester 1	N = 512	N = 146	N = 67
	0.124 (-0.222, 0.470)	-0.064 (-0.633, 0.504)	
Trimester 2	N = 512	N = 146	N = 67
	-0.008 (-0.261, 0.244)	-0.186 (-0.624, 0.253)	
Trimester 3	N = 506	N = 144	N = 65
	0.438**** (0.161, 0.716)	-0.036 (-0.525, 0.454)	
Total Gestational Weight Gain (kg, 95% CI)			
PM2.5 Exposure			
Trimester 1	N = 519	N = 148	N = 68
	0.317 (-0.099, 0.734)	-0.071 (-0.866, 0.725)	
Trimester 2	N = 519	N = 148	N = 68
	0.027 (-0.274, 0.328)	-0.409 (-1.024, 0.206)	
Trimester 3	N = 512	N = 145	N = 66
	0.445**** (0.114, 0.775)	-0.308 (-0.988, 0.372)	

*Adjusted for maternal age, race, maternal education, parity, smoking status, calendar year, and season
**Early gestational weight gain is the difference between weight at 20 weeks gestation and pre-pregnancy weight; Late gestational weight gain is the difference between last weight before delivery and weight at 20 weeks
****Gestational weight gain p-value < 0.05

Table 4. Stratum-specific gestational weight gain estimates using models with interaction by pre-pregnancy body mass index for every 5 µg/m³ higher trimester-specific PM2.5 exposure*

	Pre-Pregnancy Body Mass Index (kg/m ²)		
	Normal Weight (18.5 – 24.9)	Overweight (25.0 – 29.9)	Obese (≥30)
Early Gestational Weight Gain (kg, 95% CI)**			
PM2.5 Exposure			
Trimester 1	N = 513	N = 147	N = 67
	0.234 (-0.015, 0.483)	-0.032 (-0.363, 0.298)	
Trimester 2			
Trimester 3			
Late Gestational Weight Gain (kg, 95% CI)**			
PM2.5 Exposure			
Trimester 1	N = 512	N = 146	N = 67
	0.103 (-0.232, 0.439)	-0.076 (-0.521, 0.369)	
Trimester 2	N = 512	N = 146	N = 67
	-0.097 (-0.347, 0.153)	0.054 (-0.277, 0.386)	
Trimester 3	N = 506	N = 144	N = 65
	0.395**** (0.116, 0.674)	0.085 (-0.323, 0.494)	
Total Gestational Weight Gain (kg, 95% CI)			
PM2.5 Exposure			
Trimester 1***	N = 519	N = 148	N = 68
	0.366 (-0.060, 0.793)	-0.294 (-0.850, 0.262)	
Trimester 2	N = 519	N = 148	N = 68
	-0.085 (-0.402, 0.233)	-0.117 (-0.533, 0.300)	
Trimester 3	N = 512	N = 145	N = 66
	0.346**** (0.006, 0.698)	-0.058 (-0.573, 0.457)	

*Adjusted for maternal age, race, maternal education, parity, smoking status, calendar year, and season
**Early gestational weight gain is the difference between weight at 20 weeks gestation and pre-pregnancy weight; Late gestational weight gain is the difference between last weight before delivery and weight at 20 weeks
***Pre-pregnancy body mass index interaction p-value < 0.05
****Stratum-specific gestational weight gain p-value < 0.05

Table 5. Association of monthly PM2.5 exposure (every 5 µg/m³ higher) with early, late, and total gestational weight gain (kg) stratified by pre-pregnancy body mass index*

	Pre-Pregnancy Body Mass Index (kg/m ²)		
	Normal Weight (18.5-24.9)	Overweight (25.0-29.9)	Obese (≥30)
Early Gestational Weight Gain (kg, 95% CI)**			
PM2.5 exposure			
Month 1	N = 513	N = 147	N = 67
	0.050 (-0.302, 0.403)	0.580 (-0.083, 1.243)	
Month 2	N = 513	N = 147	N = 67
	0.065 (-0.283, 0.414)	-0.566 (-1.315, 0.182)	
Month 3	N = 513	N = 147	N = 67
	0.150 (-0.213, 0.513)	-0.382 (-1.132, 0.368)	
Month 4	N = 513	N = 147	N = 67
	0.044 (-0.285, 0.372)	-0.240 (-0.911, 0.431)	
Month 5	N = 513	N = 147	N = 67
	0.066 (-0.260, 0.392)	-0.371 (-1.127, 0.386)	
Month 6			
Month 7			
Month 8			
Month 9			
Late Gestational Weight Gain (kg, 95% CI)**			
PM2.5 Exposure			
Month 1	N = 512	N = 146	N = 67
	0.174 (-0.341, 0.690)	0.036 (-0.730, 0.802)	
Month 2	N = 512	N = 146	N = 67
	0.047 (-0.464, 0.557)	-1.091**** (-1.945, -0.237)	
Month 3	N = 512	N = 146	N = 67
	-0.203 (-0.735, 0.330)	0.307 (-0.558, 1.173)	
Month 4	N = 512	N = 146	N = 67
	-0.258 (-0.738, 0.222)	0.202 (-0.567, 0.972)	
Month 5	N = 512	N = 146	N = 67

	0.084 (-0.392, 0.561)	-0.778 (-1.639, 0.084)
Month 6	N = 511	N = 146 N = 66
	0.326 (-0.231, 0.884)	-0.375 (-1.286, 0.536)
Month 7	N = 511	N = 146 N = 66
	-0.044 (-0.536, 0.448)	-0.476 (-1.375, 0.424)
Month 8	N = 509	N = 145 N = 65
	0.009 (-0.489, 0.506)	-0.423 (-1.332, 0.486)
Month 9	N = 430	N = 124 N = 54
	0.269 (-0.299, 0.836)	0.444 (-0.519, 1.407)

Total Gestational Weight Gain (kg, 95% CI)

PM2.5 Exposure		
Month 1	N = 519	N = 148 N = 68
	0.314 (-0.300, 0.929)	0.481 (-0.601, 1.562)
Month 2	N = 519	N = 148 N = 68
	0.139 (-0.477, 0.755)	-1.737**** (-2.936, -0.538)
Month 3	N = 519	N = 148 N = 68
	0.012 (-0.629, 0.654)	-0.413 (-1.608, 0.782)
Month 4	N = 519	N = 148 N = 68
	-0.183 (-0.759, 0.394)	-0.333 (-1.405, 0.738)
Month 5	N = 519	N = 148 N = 68
	0.176 (-0.397, 0.748)	-1.360**** (-2.566, -0.153)
Month 6	N = 517	N = 147 N = 67
	0.180 (-0.482, 0.841)	-0.901 (-2.167, 0.365)
Month 7	N = 517	N = 147 N = 67
	-0.017 (-0.607, 0.573)	-0.987 (-2.236, 0.262)
Month 8	N = 515	N = 146 N = 66
	0.269 (-0.328, 0.866)	-1.109 (-2.371, 0.153)
Month 9	N = 435	N = 125 N = 55
	0.204 (-0.465, 0.873)	0.204 (-1.162, 1.570)

*Adjusted for maternal age, race, maternal education, parity, smoking status, calendar year, and season
**Early gestational weight gain is the difference between weight at 20 weeks gestation and pre-pregnancy weight; Late gestational weight gain is the difference between last weight before delivery and weight at 20 weeks
****Gestational weight gain p-value < 0.05

Table 6. Stratum-specific gestational weight gain estimates using models with interaction by pre-pregnancy body mass index for every 5 µg/m³ higher monthly PM2.5 exposure*

	Pre-Pregnancy Body Mass Index (kg/m ²)		
	Normal Weight (18.5-24.9)	Overweight (25.0-29.9)	Obese (≥30)
Early Gestational Weight Gain (kg, 95% CI)**			
PM2.5 exposure			
Month 1	N = 513	N = 147	N = 67
	0.193 (-0.186, 0.572)	0.257 (-0.215, 0.728)	
Month 2***	N = 513	N = 147	N = 67
	0.098 (-0.280, 0.478)	-0.698**** (-1.215, -0.181)	
Month 3***	N = 513	N = 147	N = 67
	0.155 (-0.235, 0.544)	-0.469 (-0.964, 0.269)	
Month 4	N = 513	N = 147	N = 67
	0.039 (-0.318, 0.396)	-0.274 (-0.741, 0.193)	
Month 5	N = 513	N = 147	N = 67
	0.039 (-0.321, 0.398)	-0.267 (-0.792, 0.258)	
Month 6			
Month 7			
Month 8			
Month 9			
Late Gestational Weight Gain (kg, 95% CI)**			
PM2.5 Exposure			
Month 1	N = 512	N = 146	N = 67
	0.118 (-0.391, 0.627)	-0.053 (-0.687, 0.581)	
Month 2	N = 512	N = 146	N = 67
	-0.159 (-0.667, 0.350)	-0.838**** (-1.535, -0.142)	
Month 3	N = 512	N = 146	N = 67
	-0.287 (-0.811, 0.238)	0.307 (-0.361, 0.975)	
Month 4	N = 512	N = 146	N = 67
	-0.322 (-0.799, 0.155)	0.400 (-0.227, 1.026)	
Month 5	N = 512	N = 146	N = 67

	-0.084 (-0.566, 0.398)	-0.294 (-1.001, 0.413)
Month 6	N = 511	N = 146 N = 66
	0.153 (-0.391, 0.697)	-0.032 (-0.756, 0.691)
Month 7	N = 511	N = 146 N = 66
	-0.099 (-0.589, 0.390)	-0.335 (-1.056, 0.387)
Month 8	N = 509	N = 145 N = 65
	0.014 (-0.479, 0.508)	-0.502 (-1.287, 0.284)
Month 9	N = 430	N = 124 N = 54
	0.406 (-0.147, 0.960)	0.220 (-0.533, 0.972)

Total Gestational Weight Gain (kg, 95% CI)

PM2.5 Exposure		
Month 1	N = 519	N = 148 N = 68
	0.419 (-0.223, 1.061)	0.013 (-0.788, 0.814)
Month 2***	N = 519	N = 148 N = 68
	-0.011 (-0.656, 0.635)	-1.695**** (-2.571, -0.819)
Month 3	N = 519	N = 148 N = 68
	-0.077 (-0.747, 0.594)	-0.432 (-1.263, 0.398)
Month 4	N = 519	N = 148 N = 68
	-0.273 (-0.882, 0.336)	-0.135 (-0.921, 0.651)
Month 5	N = 519	N = 148 N = 68
	-0.035 (-0.649, 0.579)	-0.678 (-1.571, 0.215)
Month 6	N = 517	N = 147 N = 67
	-0.130 (-0.815, 0.555)	-0.418 (-1.325, 0.490)
Month 7	N = 517	N = 147 N = 67
	-0.195 (-0.818, 0.427)	-0.614 (-1.522, 0.293)
Month 8	N = 515	N = 146 N = 66
	0.144 (-0.481, 0.768)	-0.883 (-1.875, 0.109)
Month 9	N = 435	N = 125 N = 55
	0.252 (-0.443, 0.948)	0.147 (-0.805, 1.099)

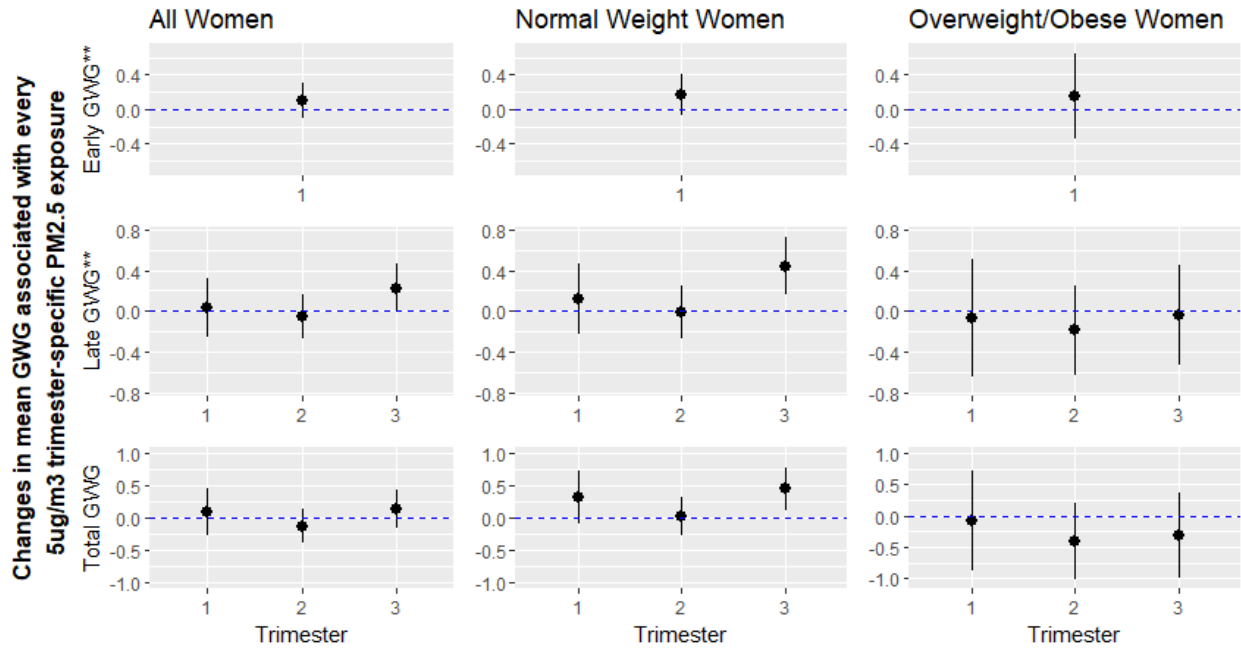
*Adjusted for maternal age, race, maternal education, parity, smoking status, calendar year, and season

**Early gestational weight gain is the difference between weight at 20 weeks gestation and pre-pregnancy weight; Late gestational weight gain is the difference between last weight before delivery and weight at 20 weeks

***Pre-pregnancy body mass index interaction p-value < 0.05

****Stratum-specific gestational weight gain p-value < 0.05

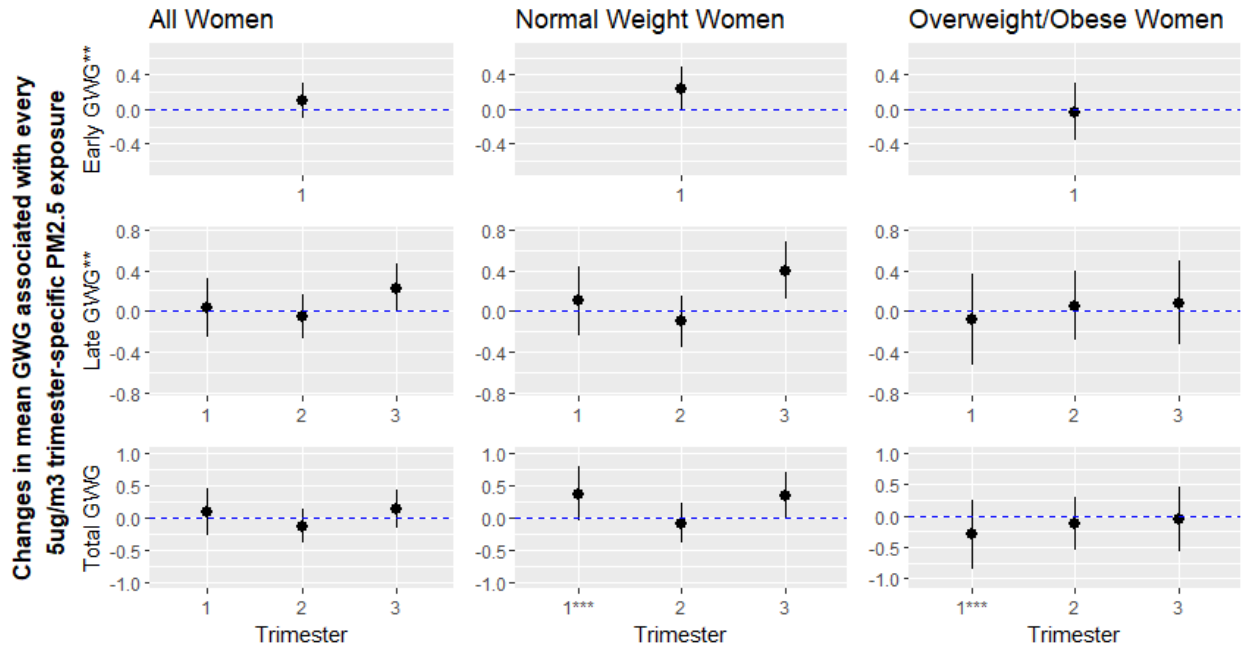
Figure 1. Associations between trimester-specific PM2.5 exposure with early, late, and total gestational weight gain (kg) stratified by pre-pregnancy body mass index*



*Adjusted for maternal age, race, maternal education, parity, smoking status, calendar year, and season

**Early gestational weight gain is the difference between weight at 20 weeks gestation and pre-pregnancy weight; Late gestational weight gain is the difference between last weight before delivery and weight at 20 weeks

Figure 2. Effect modification of gestational weight gain estimates by pre-pregnancy body mass index using models with interaction for trimester-specific PM2.5 exposure*

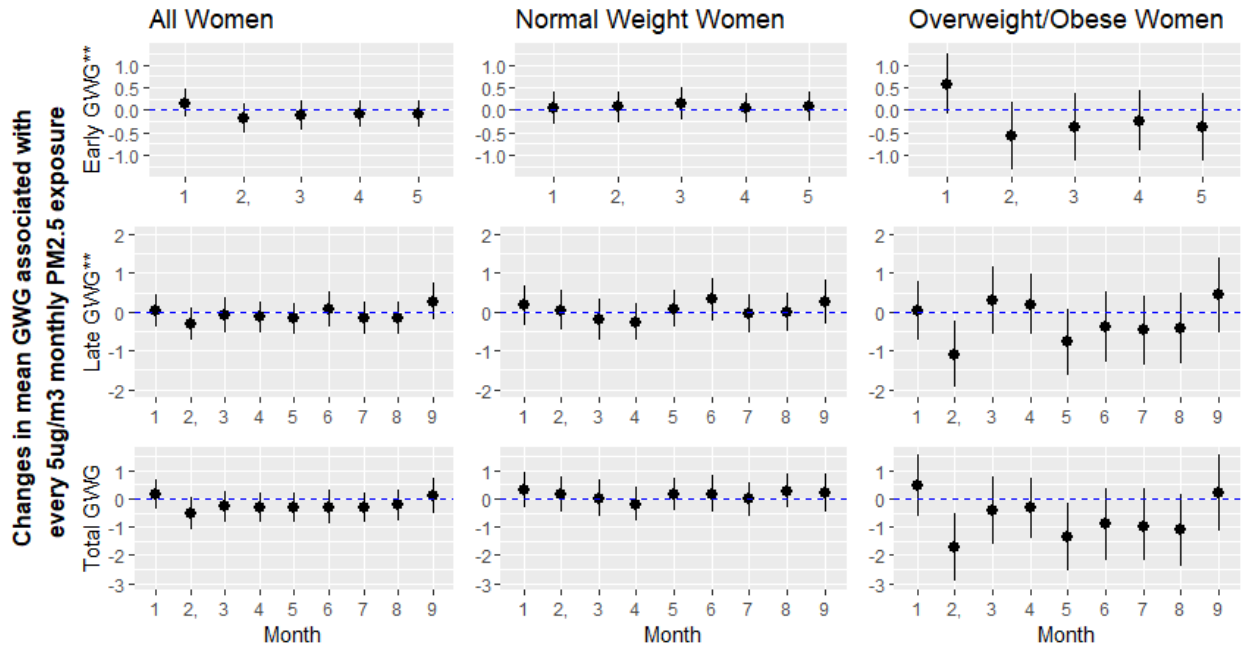


*Adjusted for maternal age, race, maternal education, parity, smoking status, calendar year, and season

**Early gestational weight gain is the difference between weight at 20 weeks gestation and pre-pregnancy weight; Late gestational weight gain is the difference between last weight before delivery and weight at 20 weeks

***Pre-pregnancy body mass index interaction p-value < 0.05

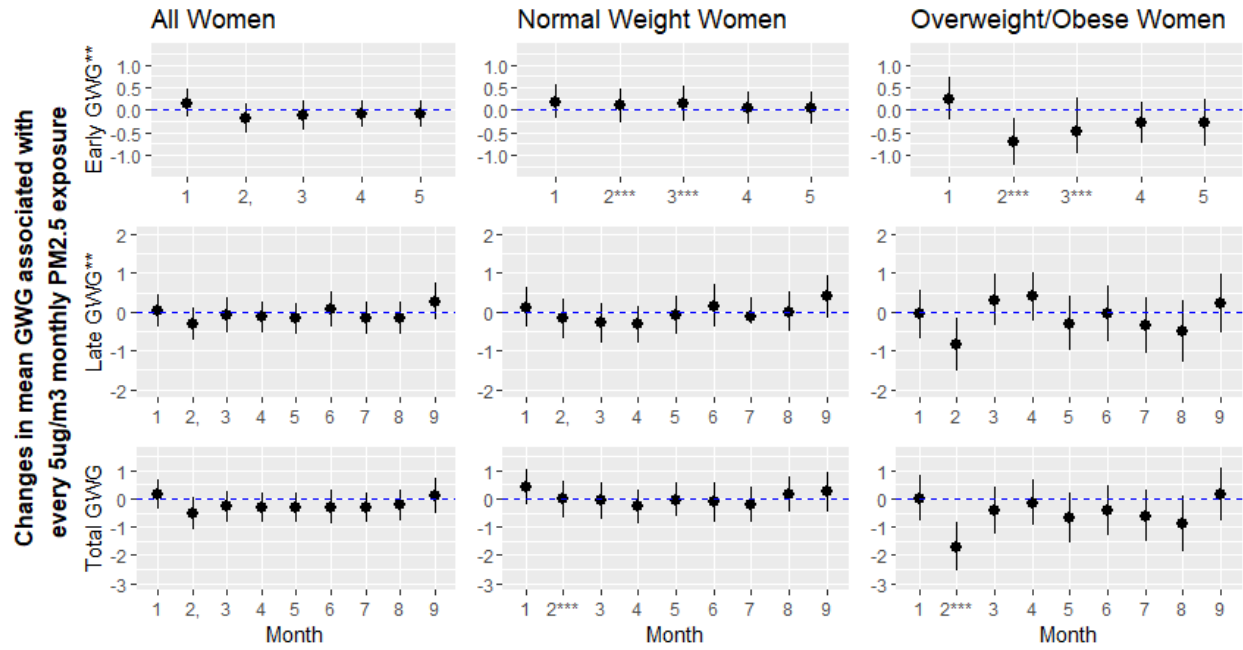
Figure 3. Associations between monthly PM2.5 exposure with early, late, and total gestational weight gain (kg) stratified by pre-pregnancy body mass index*



*Adjusted for maternal age, race, maternal education, parity, smoking status, calendar year, and season

**Early gestational weight gain is the difference between weight at 20 weeks gestation and pre-pregnancy weight; Late gestational weight gain is the difference between last weight before delivery and weight at 20 weeks

Figure 4. Effect modification of gestational weight gain estimates by pre-pregnancy body mass index using models with interaction for monthly PM2.5 exposure*



*Adjusted for maternal age, race, maternal education, parity, smoking status, calendar year, and season

**Early gestational weight gain is the difference between weight at 20 weeks gestation and pre-pregnancy weight; Late gestational weight gain is the difference between last weight before delivery and weight at 20 weeks

***Pre-pregnancy body mass index interaction p-value < 0.05

Table 7. Associations between trimester-specific and monthly PM2.5 exposure (every 5 $\mu\text{g}/\text{m}^3$ higher) with infant birth weight (g)*

PM2.5 Exposure by Trimester	Offspring Birth Weight g (95% CI)
Trimester 1	N = 774 -4.938 (-48.987, 39.111)
Trimester 2	N = 774 -6.227 (-39.229, 26.775)
Trimester 3	N = 763 102.748 (70.650, 134.847)**
PM2.5 Exposure by Months in Pregnancy	
Month 1	N = 774 -12.020 (-75.713, 51.672)
Month 2	N = 774 4.598 (-61.794, 70.991)
Month 3	N = 774 -12.205 (-79.607, 55.197)
Month 4	N = 774 -66.344 (-126.607, -6.081)**
Month 5	N = 774 -62.428 (-124.326, -0.531)
Month 6	N = 773 12.563 (-57.178, 82.313)
Month 7	N = 772 -48.828 (-110.790, 13.134)
Month 8	N = 767 31.612 (-29.914, 93.137)
Month 9	N = 648 22.906 (-39.517, 85.329)
*Adjusted for maternal age, race, maternal education, parity, smoking status, calendar year, and season	
**Offspring birth weight p-value < 0.05	

Table 8. Association between trimester-specific and monthly PM2.5 exposure ($\mu\text{g}/\text{m}^3$) with infant birth weight (g) stratified by pre-pregnancy body mass index*

	Pre-Pregnancy Body Mass Index (kg/m^2)		
	Normal Weight (18.5 – 24.9)	Overweight (25.0 – 29.9)	Obese (≥ 30)
Offspring Birth Weight (g, 95% CI)			
PM2.5 Exposure			
Trimester 1	N = 517	N = 149	N = 68
	-25.124 (-77.471, 27.223)	30.076 (-56.525, 116.677)	
Trimester 2	N = 517	N = 149	N = 68
	-29.822 (-67.663, 8.018)	43.777 (-23.993, 111.547)	
Trimester 3	N = 512	N = 146	N = 67
	110.318** (71.778, 148.858)	94.890** (29.389, 160.392)	
Offspring Birth Weight (g, 95% CI)			
PM2.5 Exposure			
Month 1	N = 517	N = 149	N = 68
	-5.830 (-82.870, 71.210)	-35.326 (-154.832, 84.180)	
Month 2	N = 517	N = 149	N = 68
	21.875 (-54.818, 98.569)	-49.523 (-183.246, 84.199)	
Month 3	N = 517	N = 149	N = 68
	-46.767 (-126.579, 32.986)	52.811 (-77.301, 182.923)	
Month 4	N = 517	N = 149	N = 68
	-86.873** (-157.791, -15.954)	-26.491 (-144.240, 91.259)	
Month 5	N = 517	N = 149	N = 68
	-87.555** (-158.183, -16.927)	-3.315 (-136.825, 130.196)	
Month 6	N = 517	N = 148	N = 68
	-18.662 (-101.467, 64.143)	-18.942 (-113.438, 151.321)	
Month 7	N = 517	N = 148	N = 68
	-45.311 (-119.043, 28.421)	4.115 (-126.820, 135.051)	
Month 8	N = 515	N = 147	N = 67
	76.504** (3.647, 149.361)	-26.227 (-153.382, 100.928)	
Month 9	N = 435	N = 126	N = 55
	7.720 (-66.624, 82.064)	19.462 (-106.783, 145.706)	
*Adjusted for maternal age, race, maternal education, parity, smoking status, calendar year, and season			
**Offspring birth weight p-value < 0.05			

Table 9. Stratum-specific birth weight estimates using models with interaction by pre-pregnancy body mass index for every 5 µg/m³ higher PM2.5 exposure*

	Pre-Pregnancy Body Mass Index (kg/m ²)		
	Normal Weight (18.5 – 24.9)	Overweight (25.0 – 29.9)	Obese (≥30)
Offspring Birth Weight (g, 95% CI)			
PM2.5 Exposure			
Trimester 1	N = 517	N = 149	N = 68
	-21.192 (-72.479, 30.094)	5.785 (-60.241, 71.811)	
Trimester 2	N = 517	N = 149	N = 68
	-19.092 (-57.318, 19.134)	6.021 (-43.525, 55.567)	
Trimester 3	N = 512	N = 146	N = 67
	107.248** (69.229, 145.266)	90.692** (35.109, 146.276)	
Offspring Birth Weight (g, 95% CI)			
PM2.5 Exposure			
Month 1	N = 517	N = 149	N = 68
	-20.961 (-97.930, 56.009)	-25.730 (-121.355, 69.896)	
Month 2	N = 517	N = 149	N = 68
	17.920 (-59.812, 95.653)	-42.662 (-147.679, 62.355)	
Month 3	N = 517	N = 149	N = 68
	-29.273 (-109.250, 50.703)	-4.004 (-101.628, 93.621)	
Month 4	N = 517	N = 149	N = 68
	-76.668** (-148.633, -4.703)	-78.162 (-170.373, 14.049)	
Month 5	N = 517	N = 149	N = 68
	-70.777 (-143.708, 2.154)	-44.718 (-148.785, 59.349)	
Month 6	N = 517	N = 148	N = 68
	7.564 (-72.597, 87.726)	-35.161 (-140.492, 70.169)	
Month 7	N = 517	N = 148	N = 68
	-35.922 (-108.732, 36.887)	-51.417 (-157.342, 54.509)	
Month 8	N = 515	N = 147	N = 67
	60.918 (-9.981, 131.818)	-22.699 (-134.850, 89.452)	
Month 9	N = 435	N = 126	N = 55
	-10.700 (-82.613, 61.213)	49.304 (-48.861, 147.469)	

*Adjusted for maternal age, race, maternal education, parity, smoking status, calendar year, and season

**Offspring birth weight p-value < 0.05

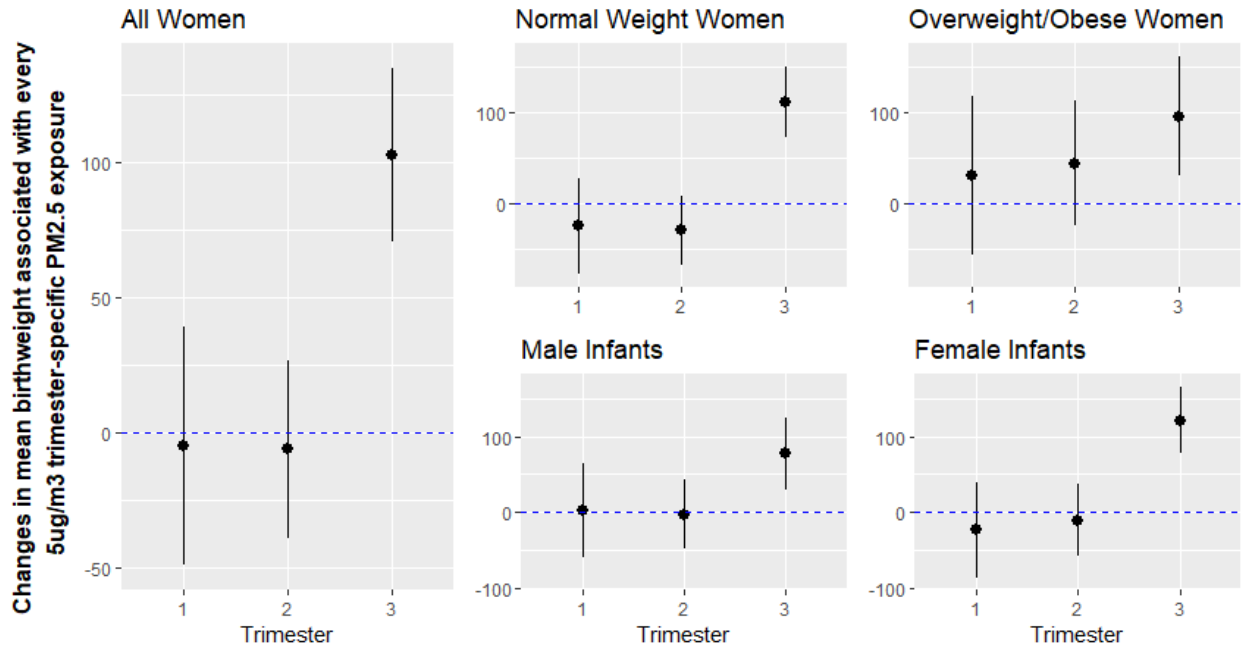
Table 10. Associations between monthly and trimester-specific PM2.5 exposure ($\mu\text{g}/\text{m}^3$) with infant birth weight (g) stratified by infant sex*

	Infant Sex	
	Male	Female
Offspring Birth Weight (g, 95% CI)		
PM2.5 Exposure		
Trimester 1	N = 394	N = 379
	2.435 (-59.736, 64.606)	-23.891 (-87.247, 39.465)
Trimester 2	N = 394	N = 379
	-2.788 (-48.846, 43.271)	-10.509 (-58.524, 37.507)
Trimester 3	N = 388	N = 374
	77.283 (30.135, 124.431)**	121.630 (78.086, 165.173)**
Offspring Birth Weight (g, 95% CI)		
PM2.5 Exposure		
Month 1	N = 394	N = 379
	-46.022 (-133.942, 41.898)	10.539 (-85.006, 106.084)
Month 2	N = 394	N = 379
	-7.929 (-100.085, 84.226)	-0.250 (-96.871, 96.371)
Month 3	N = 394	N = 379
	-2.684 (-98.519, 93.150)	-22.836 (-117.975, 72.303)
Month 4	N = 394	N = 379
	-107.465 (-194.137, -20.793)**	-19.863 (-105.019, 65.293)
Month 5	N = 394	N = 379
	-42.648 (-130.148, 44.853)	-92.059 (-179.930, -4.187)**
Month 6	N = 393	N = 379
	-58.185 (-159.373, 43.002)	82.593 (-13.380, 178.567)
Month 7	N = 393	N = 378
	-94.415 (-186.211, -2.619)**	-7.027 (-90.954, 76.900)
Month 8	N = 390	N = 376
	4.247 (-84.009, 92.502)	63.827 (-22.452, 150.107)
Month 9	N = 329	N = 318
	29.970 (-50.523, 110.464)	10.985 (-89.582, 111.553)
*Adjusted for maternal age, race, maternal education, parity, smoking status, calendar year, and season		
**Offspring birth weight p-value < 0.05		

Table 11. Stratum-specific birth weight estimates using models with interaction by infant sex for every 5 µg/m³ higher PM2.5 exposure*

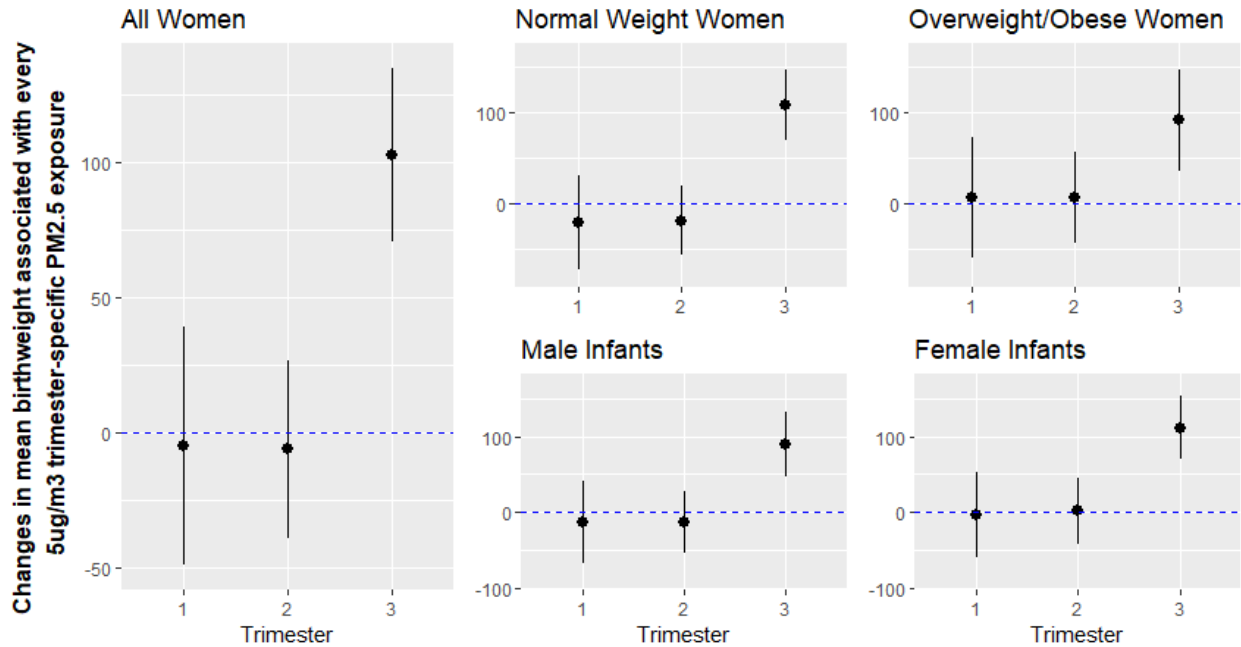
	Infant Sex	
	Male	Female
Offspring Birth Weight (g, 95% CI)		
PM2.5 Exposure		
Trimester 1	N = 394	N = 379
	-13.562 (-67.742, 40.617)	-3.833 (-60.849, 53.183)
Trimester 2	N = 394	N = 379
	-13.145 (-53.455, 27.166)	1.381 (-42.280, 45.042)
Trimester 3	N = 388	N = 374
	89.223 (46.273, 132.172)**	111.921 (70.603, 153.240)**
Offspring Birth Weight (g, 95% CI)		
PM2.5 Exposure		
Month 1	N = 394	N = 379
	-55.133 (-134.568, 24.302)	14.507 (-71.910, 100.925)
Month 2	N = 394	N = 379
	-29.234 (-113.214, 54.747)	33.663 (-56.049, 123.374)
Month 3	N = 394	N = 379
	-31.156 (-116.885, 54.573)	13.160 (-72.522, 98.843)
Month 4	N = 394	N = 379
	-113.761 (-190.403, -37.120)**	-13.586 (-94.461, 67.290)
Month 5	N = 394	N = 379
	-51.369 (-130.857, 28.119)	-82.603 (-167.566, 2.360)
Month 6	N = 393	N = 379
	-25.635 (-116.966, 65.696)	51.501 (-33.985, 136.987)
Month 7	N = 393	N = 378
	-73.803 (-155.314, 7.707)	-26.453 (-106.080, 53.174)
Month 8	N = 390	N = 376
	28.919 (-52.185, 110.023)	34.947 (-45.956, 115.849)
Month 9	N = 329	N = 318
	35.103 (-37.235, 107.442)	-6.493 (-95.298, 82.311)
*Adjusted for maternal age, race, maternal education, parity, smoking status, calendar year, and season		
**Offspring birth weight p-value < 0.05		

Figure 5. Associations between trimester-specific PM2.5 exposure with birth weight (g) stratified by pre-pregnancy body mass index and infant sex*



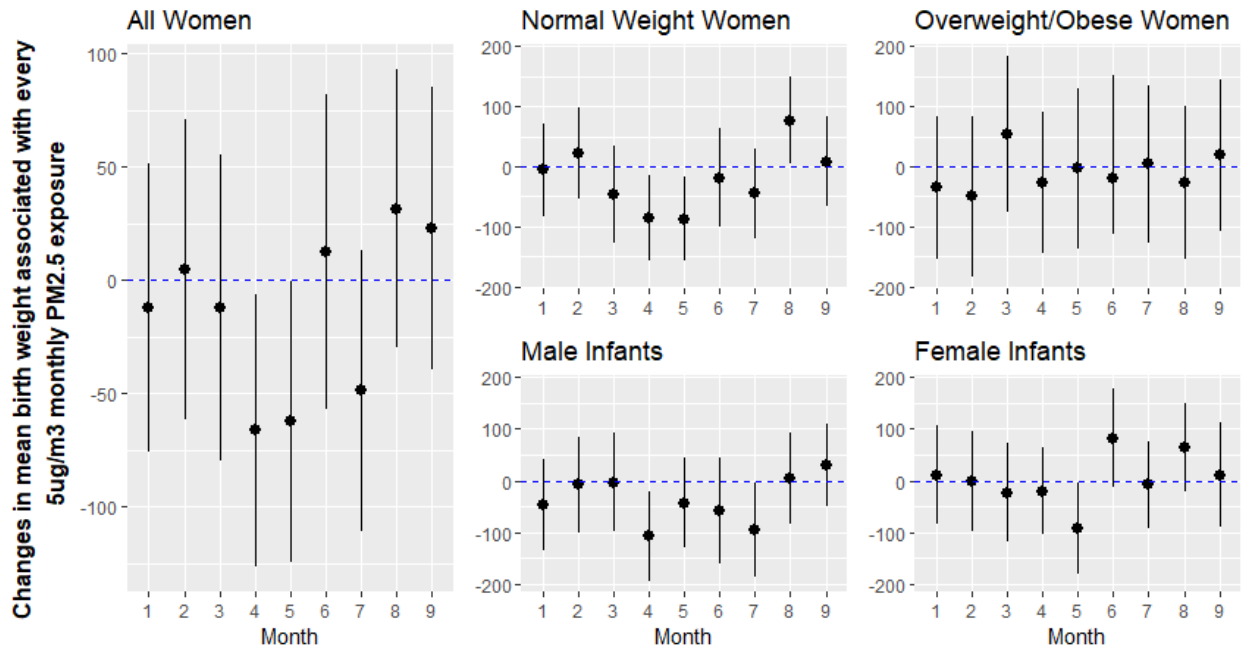
*Adjusted for maternal age, race, maternal education, parity, smoking status, calendar year, and season

Figure 6. Effect modification of birth weight estimates by pre-pregnancy body mass index and infant sex using models with interaction for trimester-specific PM2.5 exposure*



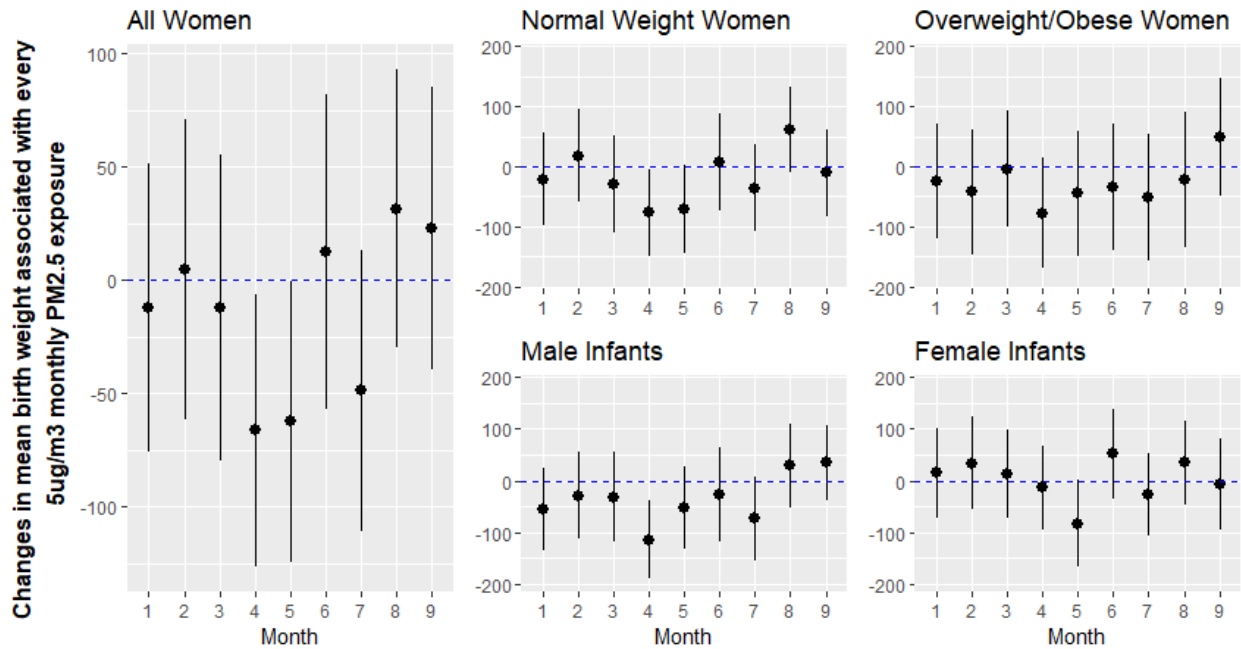
*Adjusted for maternal age, race, maternal education, parity, smoking status, calendar year, and season

Figure 7. Associations between monthly PM2.5 exposure with birth weight (g) stratified by pre-pregnancy body mass index and infant sex*



*Adjusted for maternal age, race, maternal education, parity, smoking status, calendar year, and season

Figure 8. Effect modification of birth weight estimates by pre-pregnancy body mass index and infant sex using models with interaction for monthly PM2.5 exposure*



*Adjusted for maternal age, race, maternal education, parity, smoking status, calendar year, and season

Table 12. Associations between trimester-specific and monthly PM2.5 exposure (every 5 µg/m³ higher) with early, late, and total gestational weight gain (kg) among full-term births*

PM2.5 Exposure by Trimester	Gestational Weight Gain		
	Early (N = 642)** Kg (95% CI)	Late (N = 640)** Kg (95% CI)	Total (N = 647) Kg (95% CI)
Trimester 1	0.095 (-0.131, 0.321)	0.052 (-0.241, 0.345)	0.090 (-0.281, 0.462)
Trimester 2		-0.070 (-0.296, 0.157)	-0.222 (-0.509, 0.065)
Trimester 3		0.172 (-0.096, 0.439)	0.115 (-0.222, 0.451)
PM2.5 Exposure by Months in Pregnancy			
Month 1	0.144 (-0.187, 0.474)	0.050 (-0.378, 0.478)	0.210 (-0.330, 0.749)
Month 2	-0.113 (-0.462, 0.237)	-0.337 (-0.790, 0.116)	-0.485 (-1.059, 0.090)
Month 3	-0.119 (-0.476, 0.239)	-0.022 (-0.486, 0.442)	-0.179 (-0.763, 0.404)
Month 4	-0.190 (-0.517, 0.137)	-0.152 (-0.574, 0.271)	-0.378 (-0.931, 0.135)
Month 5	-0.155 (-0.491, 0.182)	-0.185 (-0.620, 0.250)	-0.379 (-0.930, 0.171)
Month 6		0.206 (-0.295, 0.707)	-0.252 (-0.885, 0.380)
Month 7		0.090 (-0.362, 0.541)	-0.093 (-0.667, 0.482)
Month 8		-0.084 (-0.547, 0.379)	-0.301 (-0.890, 0.288)
Month 9		0.275 (-0.201, 0.751)	0.104 (-0.500, 0.707)

*Adjusted for maternal age, race, maternal education, parity, smoking status, calendar year, and season

**Early gestational weight gain is the difference between weight at 20 weeks gestation and pre-pregnancy weight; Late gestational weight gain is the difference between last weight before delivery and weight at 20 weeks

Table 13. Association of trimester-specific PM2.5 exposure (every 5 µg/m³ higher) with early, late, and total gestational weight gain (kg) stratified by pre-pregnancy body mass index among full-term births*

	Pre-Pregnancy Body Mass Index (kg/m ²)		
	Normal Weight (18.5 – 24.9)	Overweight (25.0 – 29.9)	Obese (≥30)
Early Gestational Weight Gain (kg, 95% CI)**			
PM2.5 Exposure			
Trimester 1	N = 431 0.185 (-0.062, 0.432)	N = 125 0.092 (-0.451, 0.634)	N = 54
Trimester 2			
Trimester 3			
Late Gestational Weight Gain (kg, 95% CI)**			
PM2.5 Exposure			
Trimester 1	N = 430 0.054 (-0.299, 0.407)	N = 124 0.149 (-0.449, 0.747)	N = 54
Trimester 2	N = 430 -0.018 (-0.283, 0.248)	N = 124 -0.164 (-0.649, 0.322)	N = 54
Trimester 3	N = 430 0.362*** (0.041, 0.683)	N = 124 0.012 (-0.532, 0.555)	N = 54
Total Gestational Weight Gain (kg, 95% CI)			
PM2.5 Exposure			
Trimester 1	N = 435 0.235 (-0.182, 0.653)	N = 125 0.099 (-0.735, 0.932)	N = 55
Trimester 2	N = 435 -0.006 (-0.319, 0.308)	N = 125 -0.572 (-1.246, 0.102)	N = 55
Trimester 3	N = 435 0.438*** (0.062, 0.813)	N = 125 -0.263 (-1.020, 0.495)	N = 55

*Adjusted for maternal age, race, maternal education, parity, smoking status, calendar year, and season
**Early gestational weight gain is the difference between weight at 20 weeks gestation and pre-pregnancy weight; Late gestational weight gain is the difference between last weight before delivery and weight at 20 weeks
***Gestational weight gain p-value < 0.05

Table 14. Effect modification of gestational weight gain estimates by pre-pregnancy body mass index using models with interaction for every 5 µg/m³ higher trimester-specific PM2.5 exposure among full-term births*

	Pre-Pregnancy Body Mass Index (kg/m ²)		
	Normal Weight (18.5 – 24.9)	Overweight (25.0 – 29.9)	Obese (≥30)
Early Gestational Weight Gain (kg, 95% CI)**			
PM2.5 Exposure			
Trimester 1	N = 431	N = 125	N = 54
	0.235 (-0.029, 0.499)	-0.092 (-0.449, 0.265)	
Trimester 2			
Trimester 3			
Late Gestational Weight Gain (kg, 95% CI)**			
PM2.5 Exposure			
Trimester 1	N = 430	N = 124	N = 54
	0.036 (-0.306, 0.377)	0.126 (-0.337, 0.588)	
Trimester 2	N = 430	N = 124	N = 54
	-0.096 (-0.359, 0.168)	0.003 (-0.350, 0.356)	
Trimester 3	N = 430	N = 124	N = 54
	0.374*** (0.056, 0.692)	-0.004 (-0.451, 0.444)	
Total Gestational Weight Gain (kg, 95% CI)			
PM2.5 Exposure			
Trimester 1	N = 435	N = 125	N = 55
	0.278 (-0.154, 0.709)	-0.122 (-0.695, 0.451)	
Trimester 2	N = 435	N = 125	N = 55
	-0.120 (-0.451, 0.212)	-0.314 (-0.754, 0.126)	
Trimester 3	N = 435	N = 125	N = 55
	0.368 (-0.030, 0.766)	-0.119 (-0.678, 0.440)	

*Adjusted for maternal age, race, maternal education, parity, smoking status, calendar year, and season
**Early gestational weight gain is the difference between weight at 20 weeks gestation and pre-pregnancy weight; Late gestational weight gain is the difference between last weight before delivery and weight at 20 weeks
***Gestational weight gain p-value < 0.05

Table 15. Association of monthly PM2.5 exposure (every 5 µg/m³ higher) with early, late, and total gestational weight gain (kg) stratified by pre-pregnancy body mass index among full-term births*

	Pre-Pregnancy Body Mass Index (kg/m ²)		
	Normal Weight (18.5-24.9)	Overweight (25.0-29.9)	Obese (≥30)
Early Gestational Weight Gain (kg, 95% CI)**			
PM2.5 exposure			
Month 1	N = 431	N = 125	N = 54
	-0.052 (-0.424, 0.320)	0.640 (-0.099, 1.378)	
Month 2	N = 431	N = 125	N = 54
	0.142 (-0.228, 0.512)	-0.596 (-1.479, 0.287)	
Month 3	N = 431	N = 125	N = 54
	0.281 (-0.107, 0.669)	-0.761 (-1.627, 0.105)	
Month 4	N = 431	N = 125	N = 54
	-0.013 (-0.372, 0.345)	-0.487 (-1.260, 0.286)	
Month 5	N = 431	N = 125	N = 54
	-0.007 (-0.370, 0.356)	-0.417 (-1.277, 0.443)	
Month 6			
Month 7			
Month 8			
Month 9			
Late Gestational Weight Gain (kg, 95% CI)**			
PM2.5 Exposure			
Month 1	N = 430	N = 124	N = 54
	0.060 (-0.470, 0.591)	0.212 (-0.602, 1.027)	
Month 2	N = 430	N = 124	N = 54
	-0.150 (-0.679, 0.379)	-0.868 (-1.835, 0.010)	
Month 3	N = 430	N = 124	N = 54
	-0.031 (-0.587, 0.524)	0.318 (-0.643, 1.280)	
Month 4	N = 430	N = 124	N = 54
	-0.258	0.261	

	(-0.768, 0.252)	(-0.586, 1.108)
Month 5	N = 430	N = 124 N = 54
	0.204 (-0.314, 0.722)	-1.032**** (-1.961, -0.104)
Month 6	N = 430	N = 124 N = 54
	0.518 (-0.084, 1.119)	-0.250 (-1.229, 0.730)
Month 7	N = 430	N = 124 N = 54
	0.117 (-0.423, 0.658)	0.073 (-0.892, 1.038)
Month 8	N = 430	N = 124 N = 54
	0.137 (-0.414, 0.687)	-0.339 (-1.290, 0.612)
Month 9	N = 430	N = 124 N = 54
	0.269 (-0.299, 0.836)	0.444 (-0.519, 1.407)
Total Gestational Weight Gain (kg, 95% CI)		
PM2.5 Exposure		
Month 1	N = 435	N = 125 N = 55
	0.119 (-0.502, 0.740)	0.763 (-0.381, 1.907)
Month 2	N = 435	N = 125 N = 55
	0.004 (-0.622, 0.631)	-1.525**** (-2.872, -0.178)
Month 3	N = 435	N = 125 N = 55
	0.344 (-0.312, 1.001)	-0.685 (-2.004, 0.633)
Month 4	N = 435	N = 125 N = 55
	-0.212 (-0.814, 0.391)	-0.483 (-1.657, 0.691)
Month 5	N = 435	N = 125 N = 55
	0.222 (-0.389, 0.833)	-1.652**** (-2.945, -0.359)
Month 6	N = 435	N = 125 N = 55
	0.357 (-0.356, 1.069)	-0.934 (-2.292, 0.424)
Month 7	N = 435	N = 125 N = 55
	0.146 (-0.495, 0.788)	-0.487 (-1.829, 0.854)
Month 8	N = 435	N = 125 N = 55
	0.235 (-0.418, 0.887)	-1.004 (-2.333, 0.325)
Month 9	N = 435	N = 125 N = 55
	0.204 (-0.465, 0.873)	0.204 (-1.162, 1.570)
*Adjusted for maternal age, race, maternal education, parity, smoking status, calendar year, and season		
**Early gestational weight gain is the difference between weight at 20 weeks gestation and pre-pregnancy weight; Late gestational weight gain is the difference between last weight before delivery and weight at 20 weeks		

***Gestational weight gain p-value < 0.05

Table 16. Effect modification of gestational weight gain estimates by pre-pregnancy body mass index using models with interaction for every 5 µg/m³ higher monthly PM2.5 exposure among full-term births*

	Pre-Pregnancy Body Mass Index (kg/m ²)		
	Normal Weight (18.5-24.9)	Overweight (25.0-29.9)	Obese (≥30)
Early Gestational Weight Gain (kg, 95% CI)**			
PM2.5 exposure			
Month 1	N = 431	N = 125	N = 54
	0.116 (-0.289, 0.522)	0.291 (-0.224, 0.806)	
Month 2***	N = 431	N = 125	N = 54
	0.170 (-0.236, 0.576)	-0.780**** (-1.362, -0.197)	
Month 3***	N = 431	N = 125	N = 54
	0.256 (-0.165, 0.676)	-0.715**** (-1.260, -0.169)	
Month 4	N = 431	N = 125	N = 54
	-0.024 (-0.419, 0.370)	-0.473 (-0.994, 0.048)	
Month 5	N = 431	N = 125	N = 54
	-0.034 (-0.438, 0.370)	-0.335 (-0.913, 0.243)	
Month 6			
Month 7			
Month 8			
Month 9			
Late Gestational Weight Gain (kg, 95% CI)**			
PM2.5 Exposure			
Month 1	N = 430	N = 124	N = 54
	-0.010 (-0.533, 0.513)	0.188 (-0.476, 0.853)	
Month 2	N = 430	N = 124	N = 54
	-0.355 (-0.882, 0.171)	-0.556 (-1.313, 0.200)	
Month 3	N = 430	N = 124	N = 54
	-0.175 (-0.722, 0.372)	0.355 (-0.356, 1.066)	
Month 4	N = 430	N = 124	N = 54
	-0.313	0.410	

	(-0.821, 0.195)	(-0.263, 1.083)
Month 5	N = 430	N = 124 N = 54
	0.017 (-0.503, 0.536)	-0.557 (-1.305, 0.190)
Month 6	N = 430	N = 124 N = 54
	0.405 (-0.183, 0.993)	-0.014 (-0.775, 0.747)
Month 7	N = 430	N = 124 N = 54
	0.151 (-0.383, 0.685)	-0.036 (-0.794, 0.722)
Month 8	N = 430	N = 124 N = 54
	0.223 (-0.321, 0.766)	-0.526 (-1.341, 0.288)
Month 9	N = 430	N = 124 N = 54
	0.406 (-0.147, 0.960)	0.220 (-0.533, 0.972)

Total Gestational Weight Gain (kg, 95% CI)

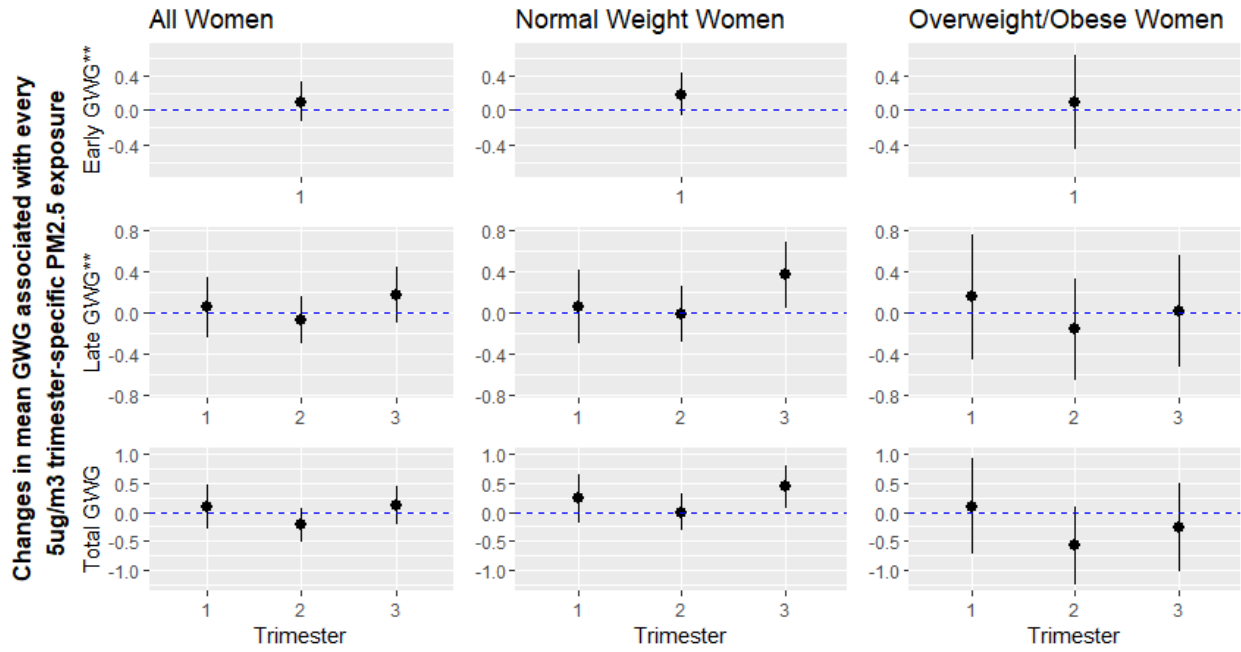
PM2.5 Exposure		
Month 1	N = 435	N = 125 N = 55
	0.233 (-0.419, 0.884)	0.335 (-0.497, 1.166)
Month 2***	N = 435	N = 125 N = 55
	-0.158 (-0.819, 0.504)	-1.464**** (-2.404, -0.523)
Month 3	N = 435	N = 125 N = 55
	0.161 (-0.529, 0.850)	-0.530 (-1.402, 0.341)
Month 4	N = 435	N = 125 N = 55
	-0.300 (-0.940, 0.341)	-0.268 (-1.100, 0.563)
Month 5	N = 435	N = 125 N = 55
	-0.004 (-0.657, 0.649)	-1.003**** (-1.933, -0.073)
Month 6	N = 435	N = 125 N = 55
	0.066 (-0.676, 0.808)	-0.454 (-1.401, 0.494)
Month 7	N = 435	N = 125 N = 55
	0.041 (-0.635, 0.716)	-0.324 (-1.270, 0.622)
Month 8	N = 435	N = 125 N = 55
	0.162 (-0.524, 0.848)	-0.916 (-1.940, 0.107)
Month 9	N = 435	N = 125 N = 55
	0.252 (-0.443, 0.948)	0.147 (-0.805, 1.099)

*Adjusted for maternal age, race, maternal education, parity, smoking status, calendar year, and season

**Early gestational weight gain is the difference between weight at 20 weeks gestation and pre-pregnancy weight; Late gestational weight gain is the difference between last weight before delivery and weight at 20 weeks

*****Pre-pregnancy body mass index interaction p-value < 0.05**
*****Gestational weight gain p-value < 0.05**

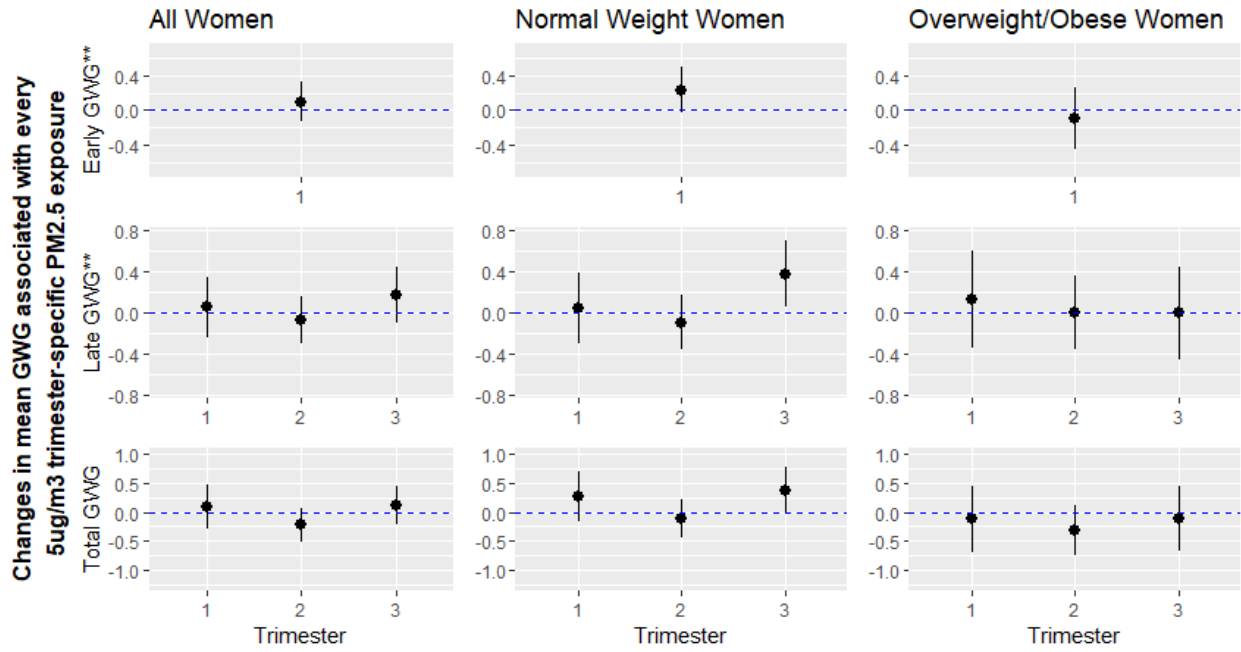
Figure 9. Associations between trimester-specific PM2.5 exposure with early, late, and total gestational weight gain (kg) stratified by pre-pregnancy body mass index among full-term births*



*Adjusted for maternal age, race, maternal education, parity, smoking status, calendar year, and season

**Early gestational weight gain is the difference between weight at 20 weeks gestation and pre-pregnancy weight; Late gestational weight gain is the difference between last weight before delivery and weight at 20 weeks

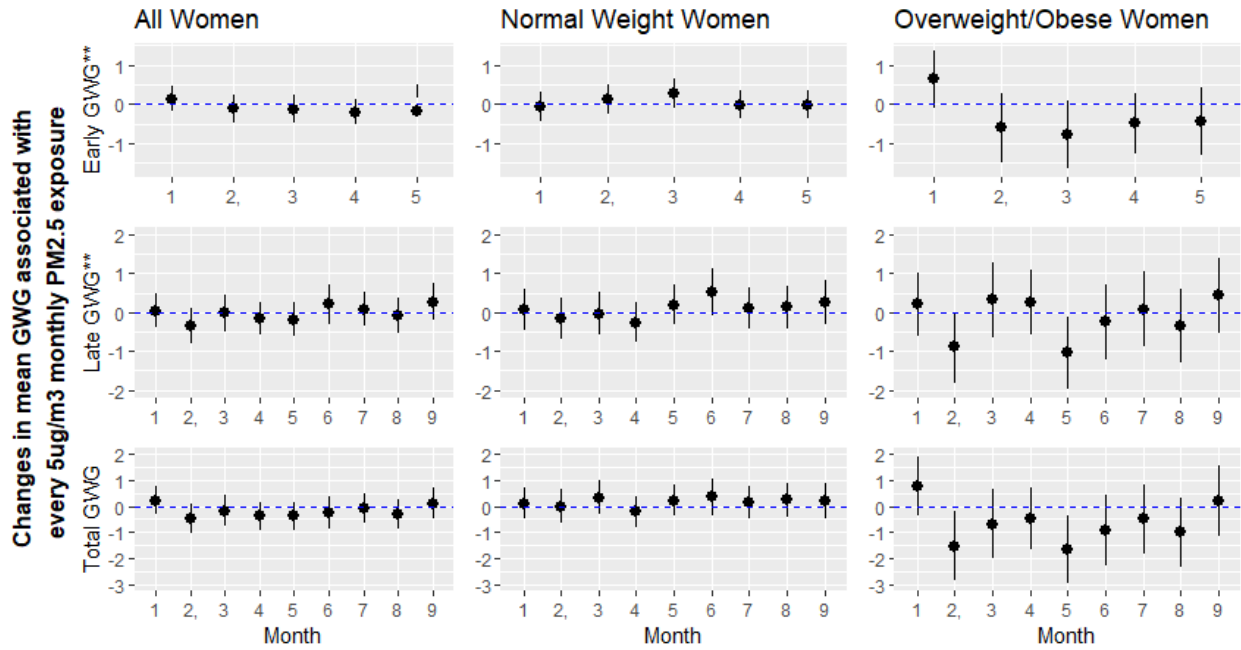
Figure 10. Effect modification of gestational weight gain by pre-pregnancy body mass index using models with interaction for trimester-specific PM2.5 exposure among full-term births*



*Adjusted for maternal age, race, maternal education, parity, smoking status, calendar year, and season

**Early gestational weight gain is the difference between weight at 20 weeks gestation and pre-pregnancy weight; Late gestational weight gain is the difference between last weight before delivery and weight at 20 weeks

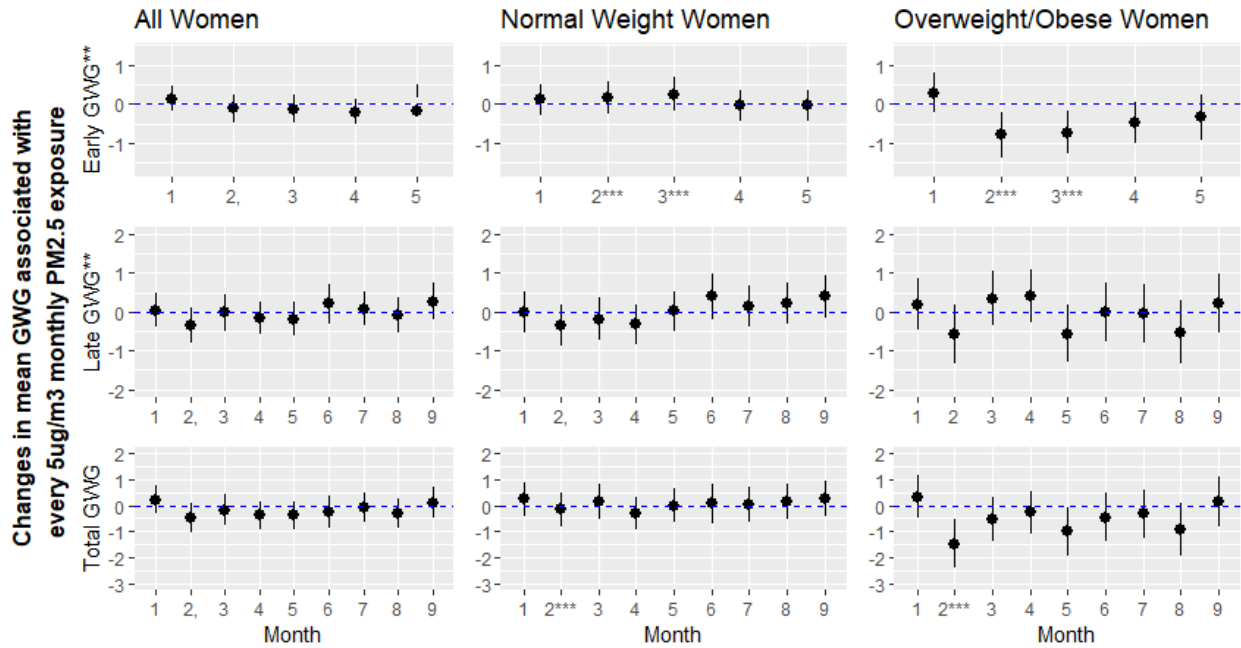
Figure 11. Associations between monthly PM2.5 exposure with early, late, and total gestational weight gain (kg) stratified by pre-pregnancy body mass index among full-term births*



*Adjusted for maternal age, race, maternal education, parity, smoking status, calendar year, and season

**Early gestational weight gain is the difference between weight at 20 weeks gestation and pre-pregnancy weight; Late gestational weight gain is the difference between last weight before delivery and weight at 20 weeks

Figure 12. Effect modification of gestational weight gain by pre-pregnancy body mass index using models with interaction for monthly PM2.5 exposure among full-term births*



*Adjusted for maternal age, race, maternal education, parity, smoking status, calendar year, and season

**Early gestational weight gain is the difference between weight at 20 weeks gestation and pre-pregnancy weight; Late gestational weight gain is the difference between last weight before delivery and weight at 20 weeks

***Pre-pregnancy body mass index interaction p-value < 0.05

Table 17. Associations between trimester-specific and monthly PM2.5 exposure (every 5 µg/m³ higher) with infant birth weight (g) among full-term births*

PM2.5 Exposure by Trimester	Offspring Birth Weight (N = 648) g (95% CI)
Trimester 1	-2.096 (-40.894, 36.701)
Trimester 2	-15.711 (-45.660, 14.238)
Trimester 3	54.276 (19.714, 88.838)**
PM2.5 Exposure by Months in Pregnancy	
Month 1	-17.274 (-73.664, 39.116)
Month 2	28.132 (-31.733, 87.997)
Month 3	4.721 (-55.977, 65.419)
Month 4	-52.970 (-108.127, 2.187)
Month 5	-49.132 (-106.251, 7.988)
Month 6	40.137 (-25.264, 105.537)
Month 7	-25.797 (-85.224, 33.629)
Month 8	20.398 (-40.554, 81.351)
Month 9	22.906 (-39.517, 85.329)
*Adjusted for maternal age, race, maternal education, parity, smoking status, calendar year, and season	
**Offspring birth weight p-value < 0.05	

Table 18. Association between trimester-specific and monthly PM2.5 exposure ($\mu\text{g}/\text{m}^3$) with infant birth weight (g) stratified by pre-pregnancy body mass index among full-term births*

	Pre-Pregnancy Body Mass Index (kg/m^2)		
	Normal Weight (18.5 – 24.9) (N = 435)	Overweight (25.0 – 29.9) (N = 126)	Obese (≥ 30) (N = 55)
Offspring Birth Weight (g, 95% CI)			
PM2.5 Exposure			
Trimester 1	-32.373 (-79.625, 14.879)	69.437 (-6.065, 144.938)	
Trimester 2	-38.009 (-73.190, -2.828)**	42.156 (-20.121, 104.433)	
Trimester 3	56.653 (15.007, 98.299)**	59.877 (-9.860, 129.614)	
Offspring Birth Weight (g, 95% CI)			
PM2.5 Exposure			
Month 1	-39.641 (-109.734, 30.452)	26.491 (-79.462, 132.443)	
Month 2	21.200 (-49.220, 91.619)	67.764 (-57.233, 192.762)	
Month 3	-39.860 (-113.685, 33.966)	66.537 (-54.289, 187.364)	
Month 4	-99.866 (-166.498, -33.234)**	41.634 (-66.833, 150.100)	
Month 5	-68.364 (-136.498, -0.230)	-7.060 (-128.795, 114.674)	
Month 6	15.873 (-63.475, 95.220)	44.565 (-81.491, 170.622)	
Month 7	-45.678 (-116.924, 25.567)	50.236 (-74.075, 174.547)	
Month 8	77.477 (5.319, 149.635)**	-68.042 (-191.525, 55.441)	
Month 9	7.720 (-66.624, 82.064)	19.462 (-106.783, 145.706)	
*Adjusted for maternal age, race, maternal education, parity, smoking status, calendar year, and season			
**Offspring birth weight p-value < 0.05			

Table 19. Effect modification of birth weight estimates by pre-pregnancy body mass index using models with interaction for every 5 µg/m³ higher PM2.5 exposure among full-term births*

	Pre-Pregnancy Body Mass Index (kg/m ²)		
	Normal Weight (18.5 – 24.9) (N = 435)	Overweight (25.0 – 29.9) (N = 126)	Obese (≥30) (N = 55)
Offspring Birth Weight (g, 95% CI)			
PM2.5 Exposure			
Trimester 1	-17.033 (-62.335, 28.268)	28.811 (-30.257, 87.879)	
Trimester 2	-24.028 (-58.825, 10.769)	1.980 (-43.286, 47.246)	
Trimester 3	51.223 (10.238, 92.208)**	62.148 (4.542, 119.755)**	
Offspring Birth Weight (g, 95% CI)			
PM2.5 Exposure			
Month 1	-33.700 (-102.157, 34.756)	0.159 (-85.742, 86.061)	
Month 2	30.501 (-39.165, 100.168)	25.810 (-71.770, 123.390)	
Month 3	-15.321 (-87.607, 56.965)	1.538 (-88.276, 91.351)	
Month 4	-75.746 (-142.194, -9.298)**	-15.880 (-101.282, 69.523)	
Month 5	-54.530 (-122.708, 13.648)	-32.063 (-127.900, 63.769)	
Month 6	25.667 (-51.211, 102.544)	26.238 (-71.250, 123.726)	
Month 7	-38.325 (-108.206, 31.556)	16.758 (-80.850, 114.367)	
Month 8	52.869 (-18.152, 123.891)	-43.403 (-149.223, 62.416)	
Month 9	-10.700 (-82.613, 61.213)	49.304 (-48.861, 147.469)	
*Adjusted for maternal age, race, maternal education, parity, smoking status, calendar year, and season			
**Offspring birth weight p-value < 0.05			

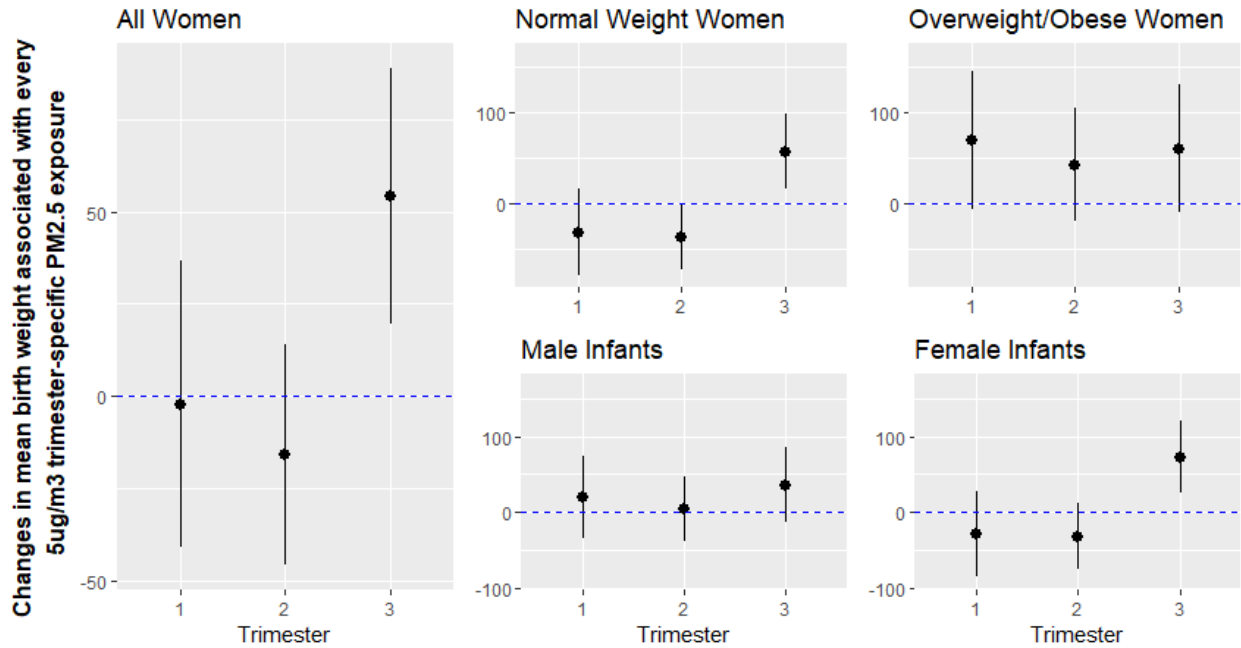
Table 20. Associations between monthly and trimester-specific PM2.5 exposure ($\mu\text{g}/\text{m}^3$) with infant birth weight (g) stratified by infant sex among full-term births*

	Infant Sex	
	Male (N = 329)	Female (N = 318)
Offspring Birth Weight (g, 95% CI)**		
PM2.5 Exposure		
Trimester 1	19.716 (-34.864, 74.295)	-29.378 (-85.816, 27.061)
Trimester 2	4.103 (-37.827, 46.033)	-32.109 (-75.721, 11.503)
Trimester 3	36.114 (-13.903, 86.132)	72.663 (24.621, 120.706)**
Offspring Birth Weight (g, 95% CI)**		
PM2.5 Exposure		
Month 1	-20.534 (-97.942, 56.874)	-28.559 (-114.294, 57.175)
Month 2	26.263 (-56.638, 109.163)	20.978 (-67.150, 109.106)
Month 3	42.037 (-44.221, 128.295)	-28.485 (-114.570, 57.599)
Month 4	-57.115 (-137.441, 23.210)	-35.238 (-113.772, 43.297)
Month 5	-26.949 (-105.710, 51.813)	-83.991 (-168.058, 0.076)
Month 6	-7.904 (-105.662, 89.854)	91.929 (3.368, 180.490)**
Month 7	-85.300 (-173.024, 2.424)	26.676 (-54.356, 107.708)
Month 8	28.456 (-59.724, 116.636)	24.616 (-61.105, 110.338)
Month 9	29.970 (-50.523, 110.464)	10.985 (-89.582, 111.553)
*Adjusted for maternal age, race, maternal education, parity, smoking status, calendar year, and season		
**Offspring birth weight p-value < 0.05		

Table 21. Effect modification of birth weight estimates by infant sex using models with interaction for every 5 µg/m³ higher PM2.5 exposure among full-term births*

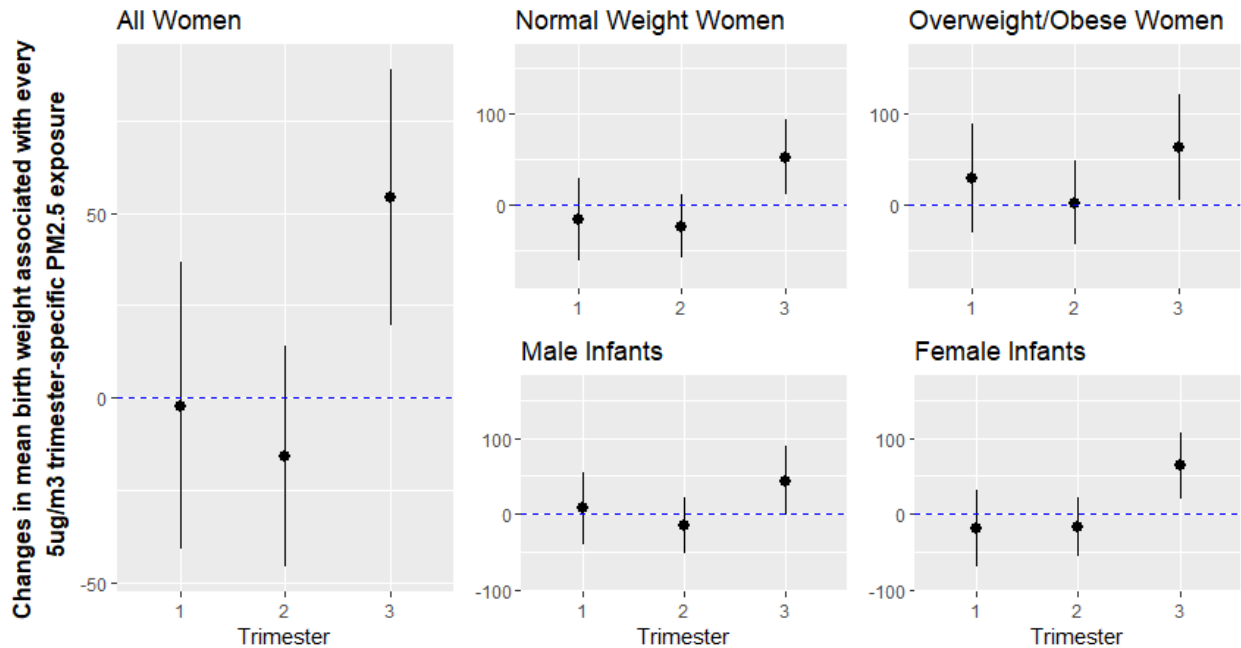
	Infant Sex	
	Male (N = 329)	Female (N = 318)
Offspring Birth Weight (g, 95% CI)		
PM2.5 Exposure		
Trimester 1	7.061 (-40.973, 55.096)	-19.259 (-68.959, 30.440)
Trimester 2	-15.092 (-51.802, 21.618)	-16.653 (-55.681, 22.374)
Trimester 3	43.702 (-1.460, 88.865)	63.682 (19.337, 108.028)**
Offspring Birth Weight (g, 95% CI)		
PM2.5 Exposure		
Month 1	-29.718 (-100.094, 40.659)	-30.018 (-105.847, 45.811)
Month 2	14.015 (-62.263, 90.292)	36.042 (-43.242, 115.327)
Month 3	12.117 (-65.883, 90.117)	2.735 (-73.323, 78.794)
Month 4	-74.918 (-145.447, -4.388)**	-29.106 (-103.009, 44.797)
Month 5	-47.272 (-118.758, 24.213)	-64.712 (-144.149, 14.726)
Month 6	3.736 (-83.281, 90.753)	79.745 (1.154, 158.337)**
Month 7	-67.606 (-145.402, 10.191)	11.632 (-63.580, 86.844)
Month 8	36.885 (-44.086, 117.857)	9.856 (-69.129, 88.840)
Month 9	35.103 (-37.235, 107.442)	-6.493 (-95.298, 82.311)
*Adjusted for maternal age, race, maternal education, parity, smoking status, calendar year, and season		
**Offspring birth weight p-value < 0.05		

Figure 13. Associations between trimester-specific PM2.5 exposure with birth weight (g) stratified by pre-pregnancy body mass index and infant sex among full-term births*



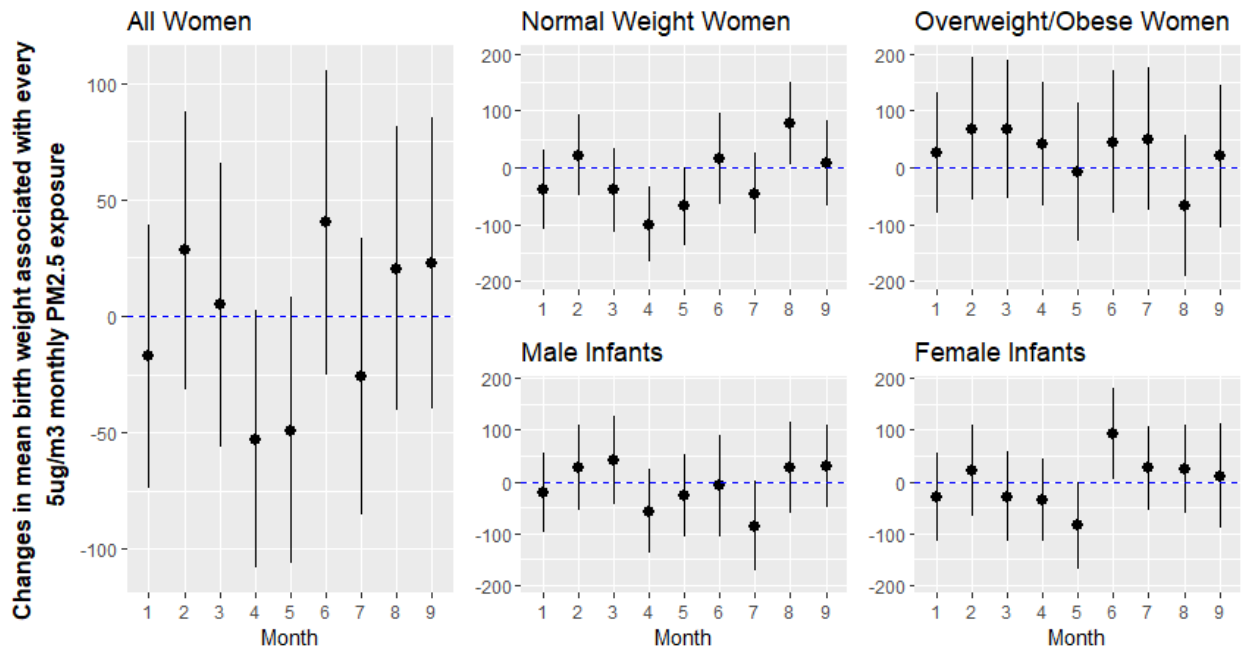
*Adjusted for maternal age, race, maternal education, parity, smoking status, calendar year, and season

Figure 14. Effect modification of birth weight by pre-pregnancy body mass index and infant sex using models with interaction for trimester-specific PM2.5 exposure among full-term births*



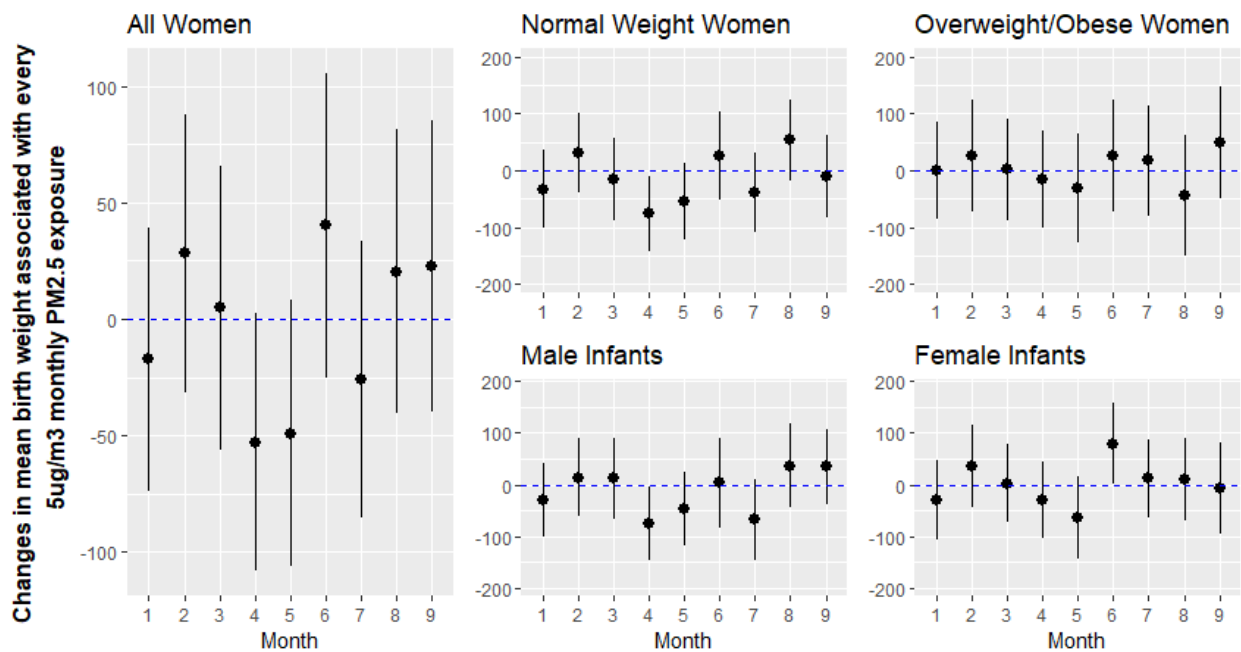
*Adjusted for maternal age, race, maternal education, parity, smoking status, calendar year, and season

Figure 15. Associations between monthly PM2.5 exposure with birth weight (g) stratified by pre-pregnancy body mass index and infant sex among full-term births*



*Adjusted for maternal age, race, maternal education, parity, smoking status, calendar year, and season

Figure 16. Effect modification by pre-pregnancy body mass index and infant sex using models with interaction for monthly PM2.5 exposure among full-term births*



*Adjusted for maternal age, race, maternal education, parity, smoking status, calendar year, and season

Table 22. Odds of excess gestational weight gain (according to Institute of Medicine guidelines) associated with 5 µg/m³ higher PM2.5 exposure*

PM2.5 Exposure by Trimester	Odds of Excess Gestational Weight Gain Odds Ratio (95% CI)
Trimester 1	N = 774 1.035 (0.871, 1.230)
Trimester 2	N = 774 1.031 (0.907, 1.172)
Trimester 3	N = 761 1.082 (0.937, 1.248)
PM2.5 Exposure by Months in Pregnancy	
Month 1	N = 774 1.191 (0.930, 1.526)
Month 2	N = 774 0.765 (0.587, 0.996)
Month 3	N = 774 1.013 (0.779, 1.316)
Month 4	N = 774 0.990 (0.781, 1.256)
Month 5	N = 774 0.999 (0.783, 1.275)
Month 6	N = 770 1.067 (0.808, 1.408)
Month 7	N = 770 1.030 (0.799, 1.327)
Month 8	N = 765 0.975 (0.748, 1.271)
Month 9	N = 647 0.964 (0.715, 1.300)
*Adjusted for maternal age, race, maternal education, parity, smoking status, calendar year, and season	

Table 23. Odds of higher early gestational weight gain rate associated with 5 µg/m³ higher PM2.5 exposure*

PM2.5 Exposure by Trimester	Odds of Higher Early Gestational Weight Gain Rate Odds Ratio (95% CI)
Trimester 1	N = 766 1.087 (0.916, 1.289)
Trimester 2	
Trimester 3	
PM2.5 Exposure by Months in Pregnancy	
Month 1	N = 766 1.071 (0.762, 1.507)
Month 2	N = 766 1.256 (0.894, 1.764)
Month 3	N = 766 0.942 (0.646, 1.375)
Month 4	N = 766 0.883 (0.625, 1.246)
Month 5	N = 766 0.990 (0.707, 1.385)
Month 6	
Month 7	
Month 8	
Month 9	

*Adjusted for maternal age, race, maternal education, parity, smoking status, calendar year, and season

Table 24. Odds of higher late gestational weight gain rate associated with 5 $\mu\text{g}/\text{m}^3$ higher PM2.5 exposure*

PM2.5 Exposure by Trimester	Odds of Higher Late Gestational Weight Gain Rate Odds Ratio (95% CI)
Trimester 1	N = 764 0.922 (0.720, 1.182)
Trimester 2	N = 764 1.022 (0.854, 1.223)
Trimester 3	N = 753 0.875 (0.716, 1.069)
PM2.5 Exposure by Months in Pregnancy	
Month 1	N = 764 1.131 (0.811, 1.576)
Month 2	N = 764 0.769 (0.534, 1.108)
Month 3	N = 764 0.688 (0.460, 1.029)
Month 4	N = 764 1.034 (0.737, 1.450)
Month 5	N = 764 1.032 (0.736, 1.447)
Month 6	N = 762 0.932 (0.638, 1.362)
Month 7	N = 762 0.826 (0.580, 1.179)
Month 8	N = 757 0.857 (0.592, 1.242)
Month 9	N = 640 0.921 (0.611, 1.390)

*Adjusted for maternal age, race, maternal education, parity, smoking status, calendar year, and season

Table 25. Odds of higher total gestational weight gain rate associated with 5 µg/m³ higher PM2.5 exposure*

PM2.5 Exposure by Trimester	Odds of Higher Total Gestational Weight Gain Rate Odds Ratio (95% CI)
Trimester 1	N = 774 1.119 (0.879, 1.425)
Trimester 2	N = 774 0.967 (0.804, 1.164)
Trimester 3	N = 761 0.838 (0.680, 1.032)
PM2.5 Exposure by Months in Pregnancy	
Month 1	N = 774 1.148 (0.818, 1.613)
Month 2	N = 774 0.716 (0.488, 1.051)
Month 3	N = 774 0.972 (0.663, 1.424)
Month 4	N = 774 1.095 (0.782, 1.535)
Month 5	N = 774 0.920 (0.646, 1.311)
Month 6	N = 770 0.822 (0.555, 1.217)
Month 7	N = 770 0.847 (0.588, 1.222)
Month 8	N = 765 0.884 (0.601, 1.302)
Month 9	N = 639 0.881 (0.566, 1.370)

*Adjusted for maternal age, race, maternal education, parity, smoking status, calendar year, and season