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IMPACTS OF BEING DOWNWIND OF A COAL-FIRED POWER PLANT ON INFANT HEALTH AT BIRTH: EVIDENCE FROM THE PRECEDENT-SETTING PORTLAND RULE

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ABSTRACT

We conduct the first study on the impacts of prenatal exposure to a uniquely identified large polluter, a coal-fired power plant located near the border of two states, on the birth outcomes of the downwind state. For mothers who live as far as 20 to 40 miles away but downwind of the power plant, being exposed to power plant emissions, in particular sulfur dioxide, during the first month of pregnancy could increase the likelihood of having full-term babies but with low birth weight, an indicator of slow fetal growth, by as much as 42 percent. This adverse impact could be driven by reactive sulfur species-induced intrauterine oxidative stress, arising from maternal exposure to emissions of sulfur dioxide, whose travelling from the emission source to the downwind region has been confirmed in the Portland Rule. In light of EPA's continual efforts in regulating power plant emissions, our study is aimed at broadening the scope of cross-border pollution analysis by taking into account adverse infant heath impacts from upwind polluters, which can burden the downwind states disproportionately.

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1 Introduction

Coal-fired power plants in the process of electricity production can put human health at greater risks than any other industrial source of air pollution (Schneider and Bank, 2010). Emissions from those power plants contain particles, mercury, and acid gases such as sulfur dioxide (SO_2), which can cause premature death (from fine particles), neurological damage (from mercury) and respiratory diseases (from acid gases).[1] To regulate power plant emissions and protect public health, the U.S. Environmental Protection Agency (EPA) has been using a four-part regulatory approach, including the Cross-State Air Pollution Rule (CSAPR, finalized in July 2011),[2] the Clean Power Plan (introduced in August 2015), the Mercury and Air Toxics Standards (MATS, finalized in December 2011), and the Acid Rain Program (ARP, started in 1995), all established under the Clean Air Act (CAA).[3]

Despite mounting evidence of public health benefits from the EPA's regulations on power plant emissions,[4] the recent U.S. Supreme Court's decision (announced on June 29, 2015) of blocking (but not striking down) the EPA's MATS highlights the importance of evaluating net benefits of regulating power plant emissions.[5] One way of improving the cost-benefit analysis needed for the EPA's regulations is to broaden the scope of external costs imposed by coal-fired power plants upon the society. For example, Currie et al. (2015) show that, besides posing health risks, toxic emissions from power plants can have significant and irreversible impacts on housing values; specifically, they find that aggregate housing values in the vicinity

[1] Source: http://www.epa.gov/airquality/powerplants (accessed July 15, 2015).

[2] The CSAPR is the replacement for the EPA's 2005 Clean Air Interstate Rule (CAIR).

[3] For detailed information about these four regulations, see http://www.epa.gov/crossstaterule (for the CSAPR), http://www2.epa.gov/cleanpowerplan (for the Clean Power Plan), http://www.epa.gov/mats (for the MATS), and http://www.epa.gov/airmarkets/programs/arp (for the ARP).

[4] For example, the CSAPR has been shown to yield "$120 to $280 billion in annual health and environmental benefits, including the value of avoiding 13,000 to 34,000 premature deaths" (Source: http://www.epa.gov/crossstaterule); for MATS: "These new standards will avert up to 11,000 premature deaths, 4,700 heart attacks and 130,000 asthma attacks every year" (Source: http://www.epa.gov/airquality/powerplanttoxics/health.html); and the ARP is shown to have effectively reduced acid deposition: "Between 1989 to 1991 and 2010 to 2012, wet deposition of sulfate decreased by 59 percent across the Eastern United States" (Source: http://www.epa.gov/airmarkets/documents/progressreports/ARPCAIR12_02.pdf, accessed July 15, 2015).

[5] http://www.nytimes.com/2015/06/30/us/supreme-court-blocks-obamas-limits-on-power-plants.html (accessed July 15, 2015).

of a toxic plant can decrease by \$4.25 million when the plant is opened, but closing the plant will not undo the loss caused by the plant's opening. Another case of external costs is the disproportionate pollution impact of coal-fired power plants due to wind: emissions from those power plants such as SO_2 and $PM_{2.5}$[6] can be carried long distances by wind, posing health risks to those who live far away but downwind of the power plants (Schneider and Bank, 2010).

Indeed, the presence of disproportionate pollution impacts between upwind and downwind states has been considered in the CAA's "Good Neighbor" Provision (i.e., Section 110(a)(2)(D)) and the "Interstate Pollution Abatement" (i.e., Section 126(b)),[7] which provide the EPA with the basis for regulations such as the CSAPR. However, continual reduction of cross-border pollution from coal-fired power plants is not without obstacles. One hindrance stems from the postponement of installing emission controls, such as the flue gas desulfurization (FGD, a.k.a. "scrubbers") for SO_2 emission controls,[8] by some of the oldest and dirtiest coal-fired power plants: "Unfortunately, not all power companies are committed to cleaning up their dirtiest plants, choosing instead to buy their way out of emissions caps." (EIP, 2007, p. 1).[9] According to the EPA's emission tracking summary, as of 2014 still only 57 percent of the coal-fired power plant units had installed the FGD for SO_2 emission controls.[10]

We conduct the first study on infant health risks posed by an upwind coal-fired power plant, a large polluter located near the border of two states, of which the pollution impact on the downwind state has been *scientifically* verified. Specifically, our study draws

[6] $PM_{2.5}$ stands for particulate matter that is smaller than 2.5 micrometers (a.k.a., microns) in diameter.

[7] For details, see http://www.epa.gov/airtransport/index.html and http://www.epa.gov/air/caa/title1.html (accessed July 15, 2015).

[8] The use of scrubbers is currently the predominant technology for removing SO_2 emissions from the exhaust of coal-fired power plants (Luechinger, 2014).

[9] Specifically, the EIP's 2007 report points out: "For example, Mirant mid-Atlantic has been silent about its cleanup plans for its three Maryland plants (Morgantown, Chalk Point, and Dickerson), even though state law requires a large reduction of sulfur dioxide no later than 2010. Other notorious polluters, like Alcoa's Warrick plant in Indiana, may be banking on their ability to avoid cleanup by purchasing pollution allowances from other states" (p. 11, http://www.dirtykilowatts.org/Dirty_Kilowatts2007.pdf, accessed July 15, 2015).

[10] Source: http://www.epa.gov/airmarkets/progress/datatrends/summary.html (accessed July 15, 2015).

evidence from a precedent-setting Portland Rule that involves the coal-fired power plant in Pennsylvania—the Portland Generating Station; the owner of the power plant—GenOn REMA, LLC (now NRG REMA, LLC); the New Jersey Department of Environmental Protection (NJDEP); the EPA; and the U.S. Court of Appeals for the Third Circuit (hereafter, the Third Circuit). The Portland Rule provides us with a rare opportunity to study infant health implications of power plant emissions for a scientifically verified impact area, where a single power plant has been confirmed by the NJDEP and the EPA to be an independent and significant air pollution contributor. In fact, the Portland Rule marks the EPA's first-ever granting of a *sole-source* petition under the "Interstate Pollution Abatement" section of the CAA, and our study is the first to utilize the Portland Rule to pinpoint the region that is affected exogenously by the power plant emissions.[11]

In contrast to Currie et al.'s (2015) study, which shows that toxic released from an industrial plant affects the air quality only within one mile of the plant, we find that power plant emissions such as SO_2, a major precursor to ambient $PM_{2.5}$ concentrations, can have adverse health impacts on infants born to mothers who live as far as 40 miles away downwind of the power plant. Specifically, among all live singleton and full-term births[12] we find that for mothers who live in the impact area identified by the NJDEP, being downwind of the power plant during their first month of pregnancy (i.e., during the embryo stage) can increase the likelihood of having low birth weight (LBW) babies (birth weight below 2,500 grams) by one percentage point, which is an approximately 42 percent increase given that the nationwide live singleton full-term LBW rate is about 2.4 percent during our sample period.[13]

[11] We give detailed discussions on our research design, including the construction of the measure for being downwind of the power plant in Sections 3.2 and 3.3.

[12] A full-term birth (a.k.a. term birth) has at least 37 completed weeks of gestation, counting from the first day of the mother's last menstrual period (Wilcox, 2001). Gestational length is commonly measured by the interval (often measured in weeks) between the first day of the mother's last menstrual period (LMP) and the date of her childbirth (Maisonet et al., 2004). Although ultrasonography is another method of measuring gestational length, it is not a substitute for the LMP-based method because of the estimation error: for instance, if a fetus has already experienced growth restrictions during the first trimester and the ultrasound taken at that time is not able to detect the slowed fetal growth, then the use of ultrasound will underestimate the actual length of *in-utero* period at the time of the measurement (Slama et al., 2008).

[13] In Section 2.3 we give detailed explanation on why our study focuses on full-term LBW.

The Portland Rule contains scientific evidence on the travel distance and direction of SO_2 emitted from the Portland Generating Station, which is about 40 miles downwind of the power plant. Within this impact area the Portland Rule also substantiates that the power plant is an independent source of air pollution and a significant contributor to the violation of air quality standards in the downwind region. Both aspects of the Portland Rule guide our research design. By focusing on the impact area identified in the Portland Rule, we are able to utilize the variation in power plant emissions that is exogenous to local pollution sources, such as vehicle exhaust worsened by traffic congestion (Currie and Walker, 2011; Ritz and Wilhelm, 2008), which can be important confounding factors in our study of the impacts of power plant emissions on infant birth outcomes.

We focus on those mothers who live at a distance to the power plant but within the impact area, to exclude possible presence of protection behaviors of those who live close to the power plant as well as selective migration away from the power plant. In fact, the impact area that we focus on belongs to the Greater New York metropolitan area, which overlaps the wealthiest part of New Jersey that is 20 to 40 miles away from the power plant. It can be reasonable to assume that the decision to live in this particular part of New Jersey largely depends on job and career opportunities that are offered in the Greater New York metropolitan area, not the distance to the power plant. Furthermore, our study period is 2004–2010, which precedes the date of the Portland Rule. As a result, those who live 20 to 40 miles away but downwind of the power plant may not have been aware of the pollution impact of the power plant during our study period.

Our study assembled a set of new evidence fully consistent with the Portland Rule, based on New Jersey's 2004–2010 birth certificate data as well as data on wind directions, power plant emissions, and mothers' residential zip codes. Specifically, we find the impacts of being downwind of the power plant on the occurrence of full-term LBW to be in the area within 40 miles of the power plant, the area including these three New Jersey counties which are not adjacent to the power plant—Hunterdon, Morris and Sussex. In contrast, the infant health impacts are not found in the area far away from the power plant: for example, in the area that is at least 80 miles away from the power plant, or in those New Jersey counties that are far away and also not directly downwind of the power plant (e.g., Cape May, Hudson and Salem Counties). We also conduct falsification checks by including leading terms of the downwind measure, and our results show no statistically significant coefficients of those terms that indicate being downwind during the months after birth on infant birth outcomes.

Using data on the power plant emissions adjusted by how downwind a New Jersey zip code is relative to the power plant, we find that the health impacts of the direction-adjusted power plant emissions follow the same pattern of the previous findings on the health impacts of being downwind of the power plant: being exposed to an increase of 1,000 tons of SO_2 emissions (which is about three percent of the power plant's annual total SO_2 emissions) from the power plant in a perfectly upwind direction during the first month of pregnancy could increase the likelihood of full-term LBW by approximately 0.24 percentage points, or by 10 percent (relative to the national level live singleton full-term LBW rate during our sample period) in the impact area that is 20 to 40 miles away from the power plant including Hunterdon, Morris and Sussex Counties. Combining the air pollution data and the power plant emission data, we further find that it is the SO_2 emissions from the power plant that significantly increase the SO_2 (a major precursor to ambient $PM_{2.5}$ concentrations) and $PM_{2.5}$ concentrations measured at each New Jersey zip code in the impact area, but not in the area far away (e.g., at least 80 miles away) from the power plant. Our analysis also suggests that it is SO_2, not NO_x (whose emissions, in addition to SO_2 emissions, are reported in the EPA's Air Markets Program Data), that has the potential to travel long distance in the air through prevailing winds.

Taken together, our results suggest an impact of *in-utero* exposure to SO_2 and $PM_{2.5}$ during the first month of pregnancy (i.e., during the embryo stage) on the occurrence of slow fetal growth, indicated by the full-term LBW. In particular, our findings on the impacts of exposure to air pollution (caused by power plant emissions) during the embryo stage on the occurrence of full-term LBW are consistent with the findings of studies by Dejmek et al. (1999), Dugandzic et al. (2006), Liu et al. (2003) and Mohorovic (2004). In general, our findings contribute to a growing body of literature investigating the critical gestation period for adverse impacts on infant health[14] from prenatal exposure to air pollution such as SO_2 and $PM_{2.5}$ due to coal-fired power plant emissions.

One potential mechanism underlying our findings on the infant health impacts from coal-fired power plants could be intrauterine oxidative stress—an excessive oxidation induced usually by an imbalance between antioxidants and cellular reactive oxygen species (ROS) production *in utero*, which can cause cellular and DNA damages. The adverse impacts of ROS-induced oxidative stress on fetal growth have been extensively studied in the medical field (Al-Gubory, Fowler and Garrel 2010; Kannan et al., 2006). However, as Giles and Jacob (2002) and Mohorovic (2004) point out, an emerging concept is that reactive sulfur species (RSS) can also contribute to oxidative stress. To the best of our knowledge, we provide the first evidence in the economics field on the adverse impact on fetal growth from possibly RSS-induced intrauterine oxidative stress due to maternal exposure to a coal-fired power plant emissions of SO_2 (a major precursor to ambient $PM_{2.5}$ concentrations) travelling to a downwind state.

Furthermore, we find that the impacts of being downwind of the power plant during the early stage of pregnancy on the occurrence of slow fetal growth are salient among males, but not among females on average. Our finding is consistent with the sex difference predicted by the theory of Developmental Origins of Health and Disease (Aiken and Ozanne, 2013) by showing that male fetuses can be more vulnerable than female fetuses to *in-utero* environmental insults (such as power plant pollutions) during the early stage of pregnancy, and the adverse impacts during the first month of pregnancy may not be overcome by the catch-up growth of male fetuses during the later stage of pregnancy.

The rest of the paper is organized as follows. Section 2 describes the empirical setting

[14] For details, see Selevan, Kimmel and Mendola (2000).

of our study and why we focus on full-term LBW, followed by Section 3, which explains the data and methods as well as our research design. Section 4 presents our empirical findings with potential biological mechanisms discussed in Section 5, and Section 6 concludes.

2 Background

2.1 Portland Generating Station

Portland Generating Station is a coal-fired power plant, formerly owned by Reliant Energy Mid-Atlantic Power Holdings, LLC. In 2010 the ownership was changed to GenOn REMA, LLC, which is a subsidiary of GenOn Energy, Inc., as a result of the merger between GenOn Power Generation, LLC and Reliant Energy Mid-Atlantic Power Holdings, LLC. In August 2013 GenOn REMA, LLC was renamed to NRG REMA, LLC[15] because of the merger between GenOn Energy Inc. and NRG Energy, Inc. completed in December 2012.[16]

Figure 1 shows the location of Portland Generating Station on a regional map of eastern Pennsylvania and western New Jersey. Located right across from Warren County, New Jersey, the power plant sits on the west bank of the Delaware River in Upper Mount Bethel Township of Northampton County, Pennsylvania.[17] According to the EPA's Emissions & Generation Resource Integrated Database (eGRID) of 2009, Portland Generating Station is one of the 43 large coal-fired power plants (defined as having a nameplate capacity of 300 megawatts or more) in the Mid-Atlantic Region,[18] and it is also one of the only two

[15] "NRG REMA, LLC, together with its subsidiaries, engages in the ownership and operation of, and contracting for power generation capacity in the United States. The company provides energy, capacity, ancillary, and other energy services to wholesale customers. The company owns or leases interests in approximately 17 generating facilities with an aggregate net electric generating capacity of 2,935 megawatts in Pennsylvania and New Jersey. The company was formerly known as GenOn REMA, LLC and changed its name to NRG REMA, LLC as a result of merger of GenOn Energy, Inc. with NRG Energy, Inc. in August 2013. The company is based in Houston, Texas. NRG REMA, LLC is a subsidiary of NRG Northeast Generation, Inc." (http://www.bloomberg.com/research/stocks/private/snapshot.asp?privcapId=3636215, accessed July 15, 2015)

[16] For details, see http://www.bizjournals.com/houston/news/2012/12/14/nrg-genon-merger-complete.html (accessed July 15, 2015).

[17] The address of the power plant is 40897 River Road, Portland, PA 18351.

[18] This refers to EPA's Region 3, which includes Delaware, District of Columbia, Maryland, Pennsylva-

large coal-fired power plants in Pennsylvania that immediately border New Jersey.[19] Figure 2 demonstrates that Portland Generating Station is in fact the only coal-fired power plant without full controls of its emissions that immediately borders New Jersey,[20] and there are no uncontrolled coal-fired power plants in New Jersey, except one near Ocean City, New Jersey, next to the Atlantic Ocean.

According to a 2007 report by the Environmental Integrity Project (EIP), Portland Generating Station was ranked fifth among the top 50 dirtiest power plants for SO_2 by emission rate (with 28.30 lbs SO_2 per MWh), and its 2006 annual SO_2 emission reached 30,685.44 tons.[21] The EIP's 2007 report also points out that a number of coal-fired power plants, such as Portland Generating Station, have been postponing the installation of scrubbers to control their SO_2 emissions. In fact, in 2009 Portland Generating Station emitted 30,465 tons of SO_2,[22] which exceeded the *combined* SO_2 emissions (of 12,810 tons) from all power generating facilities in New Jersey[23] by a significant margin (NJDEP, 2010a).

2.2 The Portland Rule

In May and September 2010 the NJDEP filed two petitions (NJDEP, 2010a and 2010b) with the EPA against Portland Generating Station, pursuant to the Section 126(b) of the Clean Air Act (CAA), which allows State A to request that the EPA should take actions against an

nia, Virginia, and West Virginia, excluding federally recognized tribes (http://www.epa.gov/tribalportal/whereyoulive/regions.htm, accessed July 15, 2015).

[19] The other coal-fired power plant is Eddystone Generating Station, which is located in the extreme southeast of Pennsylvania, near the Philadelphia International Airport. For details, see "Power Plants in the Mid-Atlantic Region," http://www.epa.gov/reg3artd/globclimate/r3pplants.html (accessed July 15, 2015).

[20] The other coal-fired power plant that immediately borders New Jersey, Eddystone Generating Station (located near Philadelphia), is a plant with controlled units. As a result, the annual SO_2 emissions from Eddystone Generating Station (8,678.00 tons) are only about 30 percent of the annual SO_2 emissions from Portland Generating Station (29,105.07 tons), according to the 2009 eGRID data (http://www.epa.gov/reg3artd/globclimate/r3pplants.html, accessed July 15, 2015).

[21] For details, see Table 3 of the 2007 report by EIP (page 12), available at http://www.dirtykilowatts.org/Dirty_Kilowatts2007.pdf (accessed July 15, 2015).

[22] For details, see "Exhibit 2: Excerpts from EPA's Clean Air Markets Emissions Database–Portland Plant's 2008/2009 Emissions" of NJDEP (2010a, pp.17–18).

[23] For details, see "Exhibit 3: Excerpts from EPA's Clean Air Markets Emissions Database–New Jersey Power Generation Facilities Total 2009 Emissions" of NJDEP (2010a, pp.19–28) and "Exhibit 4: Excerpts from EPA's Clean Air Markets Emissions Graph" of NJDEP (2010a, pp.29–30).

entity in State B if pollution from that entity causes State A to violate the National Ambient Air Quality Standards (NAAQS). The NJDEP's petitions provided scientific evidence based on air quality and aerial dispersion modeling analyses showing that Portland Generating Station is in violation of the "Good Neighbor Provision"—Section 110(a)(2)(D) of the CAA: emissions from the power plant caused SO_2 concentrations in four downwind counties of New Jersey—Warren, Sussex, Morris and Hunterdon (shown in Figure 3)—to have exceeded the SO_2 NAAQS. The May 2010 petition points out that the coal-fueled units of the power plants have no air pollution controls for SO_2 emissions and only outdated controls for nitrogen oxides and particulate matter. Furthermore, trajectory analysis reported in the September 2010 petition (which was conducted by NJDEP's Bureau of Technical Services in the second petition) demonstrates how SO_2 emissions from the power plant were transported through the air and reached the borough of Chester in Morris County, located approximately 21 miles east-southeast of the power plant.

In response to the NJDEP's petitions the EPA conducted its own independent investigation to verify the presence of impacts of the power plant emissions on the nonattainment of SO_2 NAAQS, using the American Meteorological Society/EPA Regulatory Model (a.k.a., AERMOD). On November 7, 2011, the EPA issued its final ruling—the Portland Rule (76 Fed. Reg. 69052)—concluding that the emissions from the Pennsylvania power plant *alone* caused the violations of the SO_2 NAAQS in the downwind state, New Jersey; the EPA also required the power plant to reduce SO_2 emissions by 81 percent within three years of the effective date (i.e., January 6, 2012) of the final ruling (EPA, 2011). The Portland Rule is the EPA's first-ever granting of a *sole-source* petition under the Section 126(b) of the CAA. The 2010 NJDEP petitions also mark the second-ever use of the Section 126(b) of the CAA in its history, with the prior case (i.e., *Appalachian Power Co. v. EPA,* 249 F.3d 1032) set in 1998.

On January 6, 2012, GenOn filed a petition for review with the Third Circuit, challenging the EPA's authority in imposing emission limits on the power plant.[24] On July 12, 2013, the Third Circuit issued its ruling—*GenOn REMA LLC v. EPA*, 3rd Cir., No. 12–1022, upholding the Portland Rule (United States Court of Appeals for the Third Circuit, Opinion Filed July 12, 2013).[25] The Third Circuit's ruling confirmed the validity of EPA's AERMOD analysis and supported the findings of the NJDEP and the EPA that the Portland Generating Station *alone* caused the NAAQS violations in the downwind state. On June 1, 2014, the coal-fired generating units of the power plant were shut down by its current owner, NRG REMA, LLC.[26] Since then, the power plant has become a "peak plant," running only on days when the demand for electricity is high and using low-sulfur diesel fuel to generate electricity.[27]

2.3 Our Study's Focus on Full-Term LBW

In this study we aim to identify critical windows of prenatal exposure to power plant emissions for infant health, and knowing these critical windows could improve pollution risk assessment (Selevan, Kimmel and Mendola, 2000). We examine the critical windows by month, not by trimester. As Slama et al. (2008) point out, "Most studies on IUGR [i.e., intrauterine growth restriction] used trimester-specific exposure windows. Yet when there are no strong *a priori* biologic hypotheses, investigating finer time scales (e.g., months) might be a more informative and appropriate approach" (p. 794). We use birth weight as a summary measure of a newborn's health for the reason explained by Currie (2011): birth weight is not the ideal measure for summarizing a newborn's health, but it is still widely used for that purpose because "little progress has been made toward finding an alternative, superior measure" (p.

[24] For details, see http://www.nj.gov/dep/docs/petition20120206.pdf (accessed July 15, 2015).

[25] For details of the Third Circuit's ruling, see http://www2.ca3.uscourts.gov/opinarch/121022p.pdf (accessed July 15, 2015).

[26] Source: http://www.lehighvalleylive.com/slate-belt/index.ssf/2014/05/portland_generating_station_st.html (accessed July 15, 2015).

[27] Source: http://www.lehighvalleylive.com/slate-belt/index.ssf/2014/06/portland_generating_station_sw.html (accessed July 15, 2015).

3). One important reason why we exclude preterm births[28] from our empirical analysis is that a preterm birth could be a result of maternal exposure to power plant emissions during pregnancy. If we include both preterm and full-term births into our empirical analysis, the former will confound our identification of critical windows of prenatal exposure to power plant emissions, and furthermore, we will not be able to disentangle the effect of *in-utero* exposure to power plant emissions on shortened gestational length from the effect of *in-utero* exposure to power plant emissions on slowed fetal growth. A LBW birth can be the result of either preterm or slow fetal growth, or both.

Another problem of including both preterm and full-term births into our empirical analysis comes from assigning zero values to non-exposure to power plant emissions. Note that the third trimester of a pregnancy starts at the 27th week of gestation, which is also the beginning of the seventh month of a pregnancy.[29] Thus, cases with zero values assigned to exposure to power plant emissions in the third trimester can be problematic because the pregnancies that have the third trimester can include two substantially different groups of mothers: (a) those with a seven-month gestation (i.e., preterm defined as gestational length less than 37 weeks) and (b) those with a nine-month gestation. A zero value of *in-utero* exposure for group (b) means no exposure to power plant emissions during the last phase of a *normal* pregnancy. But, a zero value of *in-utero* exposure for group (a) does not mean the same thing; instead, it means no exposure to power plant emissions during the last phase of an *abnormal* pregnancy, which is shortened from nine months to seven months. When groups (a) and (b) coexist, those cases with zero values of *in-utero* exposure assigned for the third trimester should not be used without distinction as the baseline group for the comparison of being exposed to versus not being exposed to power plant emissions. To choose the proper baseline group, we consider cases that have the same length of gestation (i.e., nine months

[28] A preterm infant is one who was born with gestational length (defined by the interval between the first day of the mother's last menstrual period and her childbirth date) shorter than 37 weeks (Maisonet et al., 2004).

[29] The first trimester includes the first 13 weeks of gestation; the second trimester covers weeks 14–26 of gestation; and third trimester starts from the 27th week of gestation.

in our study), meaning that the chosen cases all have the same length of potential exposure to power plant emissions.

By focusing on full-term births, we also aim to identify the impact of *in-utero* exposure to power plant emissions on LBW that is driven by slow fetal growth. However, including only full-term births will incur a sample selection bias: we will under-estimate the impact of *in-utero* exposure to power plant emissions on the occurrence of LBW because full-term infants under normal circumstances are healthier than preterm infants, which means fewer occurrences of LBW than what it should be for a general population. Nonetheless, an understated impact in this context could be more informative for policy considerations than an overstated impact, and we are likely to over-estimate the adverse impact of the power plant emissions if we focus only on preterm births where LBW is more prevalent than what it should be for a general population.

Despite numerous studies showing adverse impacts of LBW, few studies in the economics field have examined these two cases separately: LBW due to preterm delivery and LBW due to intrauterine growth restriction (a.k.a. intrauterine growth retardation, IUGR).[30] However, when LBW is used for evaluating pathological smallness (which is a strong predictor of infant mortality), the separation of these two cases will become important because not all preterm babies are pathologically small and full-term babies can still be pathologically small (Goldenberg and Cliver, 1997). Since pathological smallness can result from restricted growth *in utero* (i.e., IUGR) or shortened time of growth *in utero* (i.e., preterm birth), the measurement for pathological smallness should take the length of gestation into account, such as small for gestational age (SGA), which is defined as having a weight below the 10th

[30] In general, infants born with LBW can die at rates of up to 40 times those of infants born with normal weight (Goldenberg and Culhane, 2007). Almond, Chay and Lee (2005) estimate that the costs of delivery and initial care of an infant born weighing 1,000 grams can exceed $100,000 (in year 2000 dollars). LBW infants are also found to be at greater risk of developing conditions such as hypertension, cerebral palsy, and asthma during childhood (Brooks et al., 2001; Nelson and Grether, 1997); having coronary heart disease (Barker, 1995), type 2 diabetes and metabolic syndrome in adult life (Hales and Barker, 2001); as well as having lower educational attainment, poorer self-reported health status, and reduced employment and earnings (Behrman and Rosenzweig, 2004; Behrman, Rosenzweig and Taubman, 1994; Currie and Hyson, 1999).

percentile of a weight distribution for each gestational age stratum. However, using SGA as a measure for pathological smallness is not without problems for at least three reasons. First, as Wilcox (2001) points out: "At a given gestational age, births are not a random sample of all intrauterine fetuses" (p. 1239). Thus, using *birth weight* to calculate SGA (i.e., using the 10th percentile of a *birth weight* distribution) can misrepresent the actual proportion of births that are pathologically small, especially for preterm deliveries. Second, the definition of SGA essentially requires the use of fetal weight measured at each gestational age. Unlike birth weight, which can be exactly measured, antenatal fetal weight has to be inferred using fetal biometry, and the timing of conducting an ultrasonography can affect the accuracy of the inference (Yoshida et al., 2000). Third, even if antenatal fetal weight can be accurately measured, the SGA measure still can misclassify babies who are constitutionally (i.e., not pathologically) small as those who are growth-restricted due to pathological factors because the SGA measure does not take into account a fetus's genetically determined potential size.

In light of these problems associated with the SGA measure, our study focuses on LBW among full-term births (a.k.a. term LBW),[31] following Wilcox's (2001) suggestions: we exclude the influence on slow fetal growth from untimely interruptions of growth *in utero* (i.e., preterm births) by focusing on full-term births. Despite the fact that full-term LBW is a crude measure for IUGR, which like SGA will include babies who are only constitutionally (i.e., intrinsically) small, full-term LBW itself is still a distinct and important health outcome, which however has not been extensively studied in the economics field.[32] Nevertheless, adverse health effects of full-term LBW have been separately documented in the medical field. For example, using a longitudinal birth cohort study with an exclusive focus on full-term births, Caudri et al. (2007) find that children born at full term with LBW can have

[31]The birth certificate data that we obtained from the New Jersey Department of Health contain no information on fetal biometry, which prevents us from inferring fetal weight needed for the calculation of SGA.

[32]In contrast, in the medical field full-term LBW is often examined as one case of IUGR, with the assumption that "37 weeks of gestation was sufficient to reach 2500 g (5.5 pounds) and that a failure to reach this weight was indicative of IUGR" (Maisonet et al., 2004, p. 112); for example, studies using full-term LBW as a separate outcome variable include (but not limited to) Dugandzic et al. (2006), Lin et al. (2004), Maisonet et al. (2001) and Wang et al. (1997).

significantly higher risk for developing respiratory symptoms through age 5, which could be explained by a disturbed lung development due to restricted fetal growth. In addition, Wiles et al. (2005) find that it is full-term LBW, not preterm births with LBW, that is associated with having psychological distress in adulthood, and this association remains after controlling for childhood factors. They interpret this direct link between full-term LBW and adult mental health as evidence for the impacts of impaired neurodevelopment due to IUGR on adult psychiatric morbidity. Furthermore, Wiles et al.'s (2005) finding suggests that the link between impaired neurodevelopment in early life and psychological distress in adult life could be attributed to placental insufficiency, a cause for full-term IUGR, rather than other pathological factors associated with preterm births that could affect the brain.

3 Data and Methods

3.1 Data

Our study combines data from the following six sources: New Jersey Department of Health; the EPA's Air Markets Program Data (AMPD); Weather Source, LLC; the National Climatic Data Center (NCDC); the EPA's Air Quality System (AQS); and the Zip Code Database.

We obtained the 2004–2010 birth certificate data directly from New Jersey Department of Health. The birth certificate data provide us with the key information for our study, that is, birth weight and gestational length, as well as important information on the sex of the baby and the mother's age, race and ethnicity, education, marital status, and the zip code of her residence. However, in our birth certificate data there is no unique identifier for each mother, which prevents us from identifying mothers who have multiple pregnancies during our sample period (2004–2010).[33] Our study focuses on live births, which consist

[33] Because our study focuses on the impact region of the Portland Generating Station, not the entire state of New Jersey, and for the period of 2004–2010, we may not have the number of mothers who had multiple pregnancies in that region and during our sample period large enough to achieve the statistical power needed for detecting any health impacts, even if we have the identifier for each mother in the birth certificate data allowing us to use mother fixed effects.

of approximately 97% of the original data. Among those live births kept in our sample we further dropped about 6% of the sample, in which we found that the zip codes of the mothers' homes are not in New Jersey. The birth certificate data also provide us with the information on the mother's first day of her last menstrual period (LMP) and the exact birth date. We then compared our calculated difference between the birth date and the LMP with the gestational length directly reported in the birth certificate data.[34] At the end of this comparison we dropped about 0.7% of the sample where the calculated gestational length is not equal to the reported one in the birth certificate data.[35] Lastly, we kept all singleton births by dropping those cases of multiple births, about 6% of the sample[36], to exclude the cases where LBW occurs for reasons related to multiple fetuses resulting from a single pregnancy. The final number of birth records in our main estimation sample (including Hunterdon, Morris, Sussex and Warren counties) is 51,809 (reported in Table 1 and Panel A of Table 2); the final number of birth records from all New Jersey counties is 678,537 (reported in Panel B of Table 2). The key dependent variable of our study is full-term LBW, which is defined as infant birth weight below 2,500 grams while gestational length is greater than or equal to 37 weeks.

From AMPD we extracted the Portland Generating Station's daily emission data.[37] In AMPD the following three categories of power plant emissions are reported: sulfur dioxide (SO_2, measured in tons), nitrogen oxides (NO_x, measured in tons) and carbon dioxide (CO_2, measured in short tons).[38] For some of the additional analyses explained in Section 4.3 we

[34]The gestational length directly reported in the birth certificate data is based on the difference between the mother's LMP and the birth date.

[35]This gestational length directly reported in the birth certificate data is measured in weeks and in integers. When we calculated the gestational length ourselves for the comparison, we used (a) the mother's LMP and (b) the exact birth date; then used (b) minus (a); then divided the difference by seven; and then rounded the result to the nearest integer.

[36]Furthermore, we dropped the observations in the birth certificate data (i) where the year of LMP is shown to be 2002 or earlier; (ii) where the gestational length is either shorter than 13 weeks or longer than 45 weeks; and (iii) where the birth weight information is indicated by the New Jersey Department of Health as to be followed up for verification. Note that (i) and (ii) consist of approximately 1% of the sample, and (iii) consists of 0.55% of the sample.

[37]The AMPD's power plant emission data are available at http://ampd.epa.gov/ampd/. The earliest year of Portland Generating Station's emission data is 1995.

[38]Our study does not focus on carbon dioxide emissions from the power plant, mainly because carbon

also extracted the hourly SO_2 emission data (measured in pounds) from AMPD for each day from January 1 to December 31 and for each year from 2004 to 2010.

To have the information on hourly wind directions near the power plant, we purchased a database at Weather Source, LLC,[39] from which we selected the Allentown Lehigh Valley International Airport weather station. This weather station is located in Pennsylvania, southwest of the power plant. We selected this weather station because it is the one closest to the power plant that has a complete series of records on hourly wind directions every day since January 1, 1960.[40] The wind direction reported in this weather database is a continuous variable measured in degrees ranging from 0 to 360, with 0-degree (or 360-degree) indicating the wind comes from due North and accordingly, 90-degree for due East, 180-degree for due South, and 270-degree for due West.

In addition to the hourly wind direction data, we obtained monthly weather data from all weather stations in New Jersey from the NCDC's Global Historical Climatology Network Database (GHCND). The weather variables that we extracted from the GHCND are monthly high temperature, monthly low temperature, monthly mean temperature, monthly rainfall and monthly snowfall.[41]

From AQS we retrieved data on SO_2, $PM_{2.5}$ and NO_2 concentrations measured by the EPA's monitors placed in New Jersey and the adjacent states including Delaware, Maryland, New York and Pennsylvania.[42] In our retrieved AQS data, SO_2 concentrations are represented by the one-hour daily maximum readings by the EPA's monitors for SO_2, measured in

dioxide is one of the greenhouse gases and it is not among the six common air pollutants (i.e., carbon monoxide, lead, nitrogen dioxide, ozone, particulate matter, and sulfur dioxide) for which the Clean Air Act requires the EPA to set NAAQS.

[39] Detailed descriptions of the weather data provided by the Weather Source, LLC, are provided at http://weathersource.com/.

[40] This weather station is also included in the wind fields analysis provided in the May 2010 NJDEP's petition.

[41] There are 427 New Jersey weather stations in this GHCND dataset. The weather variables in this dataset are measured on a monthly basis, and there is no information on wind. The monthly high (monthly low, or monthly mean) temperature is the monthly mean minimum (monthly mean maximum, or monthly average) temperature derived by the GHCND from daily minimum (daily maximum, or daily average) temperature.

[42] The EPA's AQS data are available at http://aqsdr1.epa.gov/aqsweb/aqstmp/airdata/download_files.html.

parts per billion (ppb);[43] $PM_{2.5}$ concentrations are represented by the daily maximum readings by the EPA's monitors for $PM_{2.5}$, measured in microgram per cubic meter ($\mu g/m^3$);[44] and NO_2 concentrations are represented by the one-hour daily maximum readings by the EPA's monitors for NO_2, measured in parts per billion (ppb).[45]

Lastly, we purchased a zip code database that includes all of the 723 New Jersey zip codes.[46] This database provides us with the exact latitudinal and longitudinal coordinates of each New Jersey zip code centroid; we merged these coordinates into the New Jersey birth certificate data for the zip code of every mother's residence.

3.2 Construction of Variables

We use the following four-step procedure to construct a variable representing a geographic area located downwind of the Portland Generating Station; hereafter, we call this variable "being downwind of the power plant," which varies by each New Jersey zip code and also varies monthly from January 2004 to December 2010.

First, we calculate the direction in which each New Jersey zip code centroid is located relative to the power plant. This calculation uses the latitudes and longitudes of two points—the power plant[47] and each New Jersey zip code centroid, with the earth's surface taken into account. Throughout our study we use *azimuth*, which is an angle between point A and

[43] The ppb measures the concentration of a gaseous pollutant by its volume per 10^9 volumes of ambient air.

[44] The $\mu g/m^3$ (microgram per cubic meter) measures the concentration of a gaseous pollutant in units of mass (μg) per volume (m^3) of ambient air.

[45] For $PM_{2.5}$ we retrieved the data measured by the Federal Reference Methods (FRM) because it is the $PM_{2.5}$ measured by the FRM (i.e., the category "88101" coded by the EPA), not the non-FRM (i.e., "88502" coded by the EPA), that is used for the evaluation of $PM_{2.5}$ NAAQS attainment. For detailed explanations on FRM, see http://www.epa.gov/ttn/airs/airsaqs/memos/PM-cont-Reporting-Tech-Note-053106.pdf (accessed July 15, 2015). For $PM_{2.5}$ we use the daily monitor readings because NAAQS's primary and secondary standards regulate $PM_{2.5}$ concentrations at the 24-hour level. We retrieved from the AQS the data on one-hour daily maximums for SO_2 and NO_2 because they are used to evaluate attainment of the NAAQS primary standards for SO_2 and NO_2. For details on NAAQS, see http://www.epa.gov/air/criteria.html (accessed July 15, 2015).

[46] For detailed descriptions of this database, see http://www.zip-codes.com/zip-code-statistics.asp (accessed July 15, 2015).

[47] We obtained latitude (i.e., +40.91) and longitude (i.e., −75.0789) of the Portland Generating Station from the EPA's AMPD.

point B in a spherical coordinate system (expressed in degrees), as the measure for direction. To calculate the azimuth of point B (the point of interest, such as a New Jersey zip code centroid) from point A (the origin, such as the power plant), we project the vector $\overrightarrow{\mathrm{AB}}$ onto a horizontal plane. On that horizontal plane, the reference vector is due North, which is used for point A (the origin) and has an azimuth of 0 or 360 degrees; moving clockwise on a 360-degree circle, a point due East has an azimuth of 90 degrees, and accordingly, 180 degrees for due South and 270 degrees for due West. The azimuth of point B from point A is given by the angle between the projected vector of $\overrightarrow{\mathrm{AB}}$ and the reference vector on that horizontal plane.[48] For example, the direction in which New York City is located from Chicago can be expressed by the azimuth of 91.95 degrees (i.e., east-southeast of Chicago); the direction in which Vancouver (of Canada) is located from Chicago can be expressed by the azimuth of 298.93 degrees (i.e., west-northwest of Chicago).

In the second step we convert the wind direction from being measured as where the wind comes from (based on the meteorological definition in the weather database) to being measured as where the wind blows, that is, the *wind vector azimuth*: we subtract 180 degrees from the direction from which the wind comes, and we will add 360 degrees if the subtraction results in a negative value. We use the wind vector azimuth throughout our study to be consistent with the measurement of the direction of each New Jersey zip code relative to the power plant, near which we consider the direction toward which the wind blows. It is also worth noting that in meteorology a wind blowing eastward is called a *westerly* wind.

In the third step we use *vector means*, not arithmetic means, for the calculation of daily average wind direction using the hourly wind direction data we obtained from Weather Source, LLC. Wind direction data are examples of "circular" data, where both the start value (0 degree) and end value (360 degree) indicate exactly the same direction. Ignoring this fact can result in serious mistakes when calculating an average wind direction. For

[48] The azimuth of point A from point B is given by the angle between the projected vector of $\overrightarrow{\mathrm{BA}}$ and the reference vector on that horizontal plane. It is different from the azimuth of point B from point A by 180 degrees.

example, based on the meteorological definition, both a 5-degree wind and a 355-degree wind can be regarded as a northerly wind, and so should be the average of the two; however, the arithmetic mean of 5 degrees and 355 degrees is 180 degrees, which indicates a southerly wind, not a northerly wind that should have been the result of averaging two northerly winds. In contrast to the arithmetic mean, the vector mean of 5 degrees and 355 degrees is 0 degree (or 360 degrees).

In the fourth step we calculate a *cosine* function of the difference between each New Jersey zip code centroid azimuth (θ_1) and the wind vector azimuth near the power plant (θ_2), that is, the cosine function of the direction of a New Jersey zip code centroid relative to the power plant minus the direction toward which the wind blows near the power plant (i.e., $\cos(\theta_1 - \theta_2)$), for each day from January 1, 2003 (one year before the first year of our birth certificate data) to December 31, 2010 (the last year of our birth certificate data). We use the value of this cosine function as a continuous measure for how downwind a New Jersey zip code is, on a daily basis, relatively to the power plant: a zero-degree (or a 180-degree) difference gives the cosine function the maximum (or the minimum) value of 1 (or -1), which is used to indicate a perfectly downwind (or perfectly upwind) location relative to the power plant.[49] Next, we average the daily values of this cosine function for each New Jersey zip code-year-month pair, to make it vary monthly by each New Jersey zip code.

In some of our analyses we use direction-adjusted sulfur dioxide (or nitrogen oxides) emissions from the power plant. They are measured by first taking the product of the daily sulfur dioxide (or nitrogen oxides) emissions from the power plant (reported in the AMPD) and the cosine function of the difference between daily wind direction (where the wind blows) near the power plant and the azimuth of New Jersey zip code centroid (relative to the power plant), and then aggregating the aforementioned product to the zip code-monthly level. This construction of the direction-adjusted power plant emissions assumes that, all else being equal, pollution impacts from the power plant will increase if a zip code is more

[49] Note that $0 \leqslant \cos\omega \leqslant 1$ when $0° \leqslant \omega \leqslant 90°$ and $-1 \leqslant \cos\omega < 0$ when $90° < \omega \leqslant 180°$.

downwind of the power plant.

In addition to the variables indicating how downwind (relative to the power plant) each New Jersey zip code is and the associated direction-adjusted (SO_2 and NO_x) emissions from the power plant, we construct zip code-level monthly pollution variables for SO_2, NO_2 and $PM_{2.5}$ using the AQS data, as well as zip code-level monthly weather variables using the NCDC data.

To construct those pollution variables we use the following four-step procedure. In the case of SO_2 we first compute a monthly simple average of SO_2 concentration for each SO_2 monitor, using the one-hour daily maximum readings. Second, we pair each New Jersey zip code with all SO_2 monitors. Using the latitudinal and longitudinal coordinates of each zip code centroid and each SO_2 monitor, we calculate the *geodetic (a.k.a., geodesic) distance* between each zip code centroid and each paired SO_2 monitor. The geodetic distance approximates the length of the shortest curve between two points along the surface of the earth.[50] Third, based on the geodetic distance, we select those SO_2 monitors located within 20 miles of the zip code centroid. Fourth, we compute the zip code-level monthly SO_2 concentration, which is the weighted average of the monthly SO_2 concentrations obtained in the first step (i.e., the monitor-level monthly simple averages of SO_2 concentrations), including readings for monitors within our chosen radius of the zip code centroid. The weight is equal to the inverse of the geodetic distance between the zip code centroid and the paired SO_2 monitor. Our use of the inverse-distance weighting method, as well as our chosen radius of 20 miles, follows Currie and Neidell (2005).[51] We repeat this four-step procedure for NO_2 and $PM_{2.5}$ to get the zip code-level monthly variables.[52]

To construct zip code-level monthly weather variables we use the following three-step procedure. First, we pair each New Jersey zip code with all weather stations in New Jersey that are included in NCDC's GHCND. Using the latitudinal and longitudinal coordinates of each

[50] We use *geodetic distance* for all the distance calculations in this paper.

[51] We also use a 15-mile radius for robustness checks.

[52] Summary statistics of the pollution variables are reported in Appendix Table 2.

zip code centroid and each weather station, we calculate the geodetic distance between the zip code centroid and each paired weather station. Second, based on the geodetic distance, we select those weather stations located within 20 miles of the zip code centroid.[53] Third, we compute the zip code-level monthly-measured weather variable, which is the weighted average of the monthly-measured weather variable provided by NCDC's GHCND within our chosen radius of the zip code centroid. The weight is equal to the inverse of the geodetic distance between the zip code centroid and the paired weather station.[54]

3.3 Selection of Estimation Sample

Among the four New Jersey counties identified in the NJDEP's petitions, we focus on these three counties: Hunterdon, Morris and Sussex. These three counties all belong to the New York-Northern New Jersey-Long Island Metropolitan Statistical Area (MSA), and they are 20 to 40 miles away from the Portland Generating Station. The decision to live in one of these three counties may largely depend on the job and career opportunities that are available in the New York-Northern New Jersey-Long Island MSA, not on the distance to the power plant. As a result, the behavior of avoiding the power plant in residential choice can be largely precluded. One implication of this focus is that our study's findings may not be valid for other states or other counties of New Jersey, since we focus on a wealthy state and also a wealthy part of the state.[55] However, this focus also implies that our finding on adverse impacts of power plant emissions on infant health based on a wealthy part of the United States are more likely to be an under-estimation than an over-estimation, because residents of that wealthy region have higher income than the general population, and higher income can be associated with better access to health care, which tends to reduce the occurrence of adverse birth outcomes. In the evaluation of adverse impacts of power plant emissions, an

[53] We also use a 15-mile radius for robustness checks.

[54] Summary statistics of the weather variables are reported in Appendix Table 2.

[55] According to the U.S. Census Bureau, median household income (2009–2013) is $106,143 in Hunterdon County, $98,633 in Morris County, $87,335 in Sussex County, and $70,912 in Warren County, all except Warren exceeding the New Jersey average of $71,629 and all four counties exceeding the national average of $53,046 (Source: http://quickfacts.census.gov/qfd/states/, accessed July 15, 2015).

under-estimation can be more informative than an over-estimation to policy-makers, when a lower bound of the actual adverse impacts is preferred to an upper bound.

3.4 Regression Models

For our main analyses we use the following regression models:

$$\begin{aligned} y_{i,jt} &= \alpha_0 \text{downwind}_{jt} + \alpha_1 \text{downwind}_{j,t-1} + \cdots + \alpha_8 \text{downwind}_{j,t-8} + \\ &\quad \mathbf{x}_i' \beta + \text{zip code}_j + \text{monthly}_t + \text{error term}_{i,jt}. \end{aligned} \tag{1}$$

In equation (1) $y_{i,jt}$ is a binary indicator, equal to one for full-term LBW and zero otherwise, for infant i whose mother lives in a New Jersey zip code j; the subscript t indexes the year and month, ranging from January 2004 to December 2010, during which infant i was born. We use a comma between the subscripts i and jt to emphasize the fact that our data are not longitudinal for infant i's mother over time.

The construction of the "downwind" variable uses the four-step procedure explained in Section 3.2. Our estimation sample includes live singleton full-term births only (i.e., live singleton births with gestational length greater than or equal to 37 weeks). A normal pregnancy is usually 39 to 40-week long, which is 9-month long.[56] Accordingly, we include nine "downwind" terms for each of the nine months of a full-term pregnancy, aiming to disentangle the impacts of being downwind of the power plant during the early stage of pregnancy from those during the late stage of pregnancy.

The control variables $\mathbf{x}_i$ include infant i's sex, male (0) or female (1); infant i's mother's age; dummy variables (1/0) for the mother's race and ethnicity (White, Black, Hispanic); having completed a four-year college or higher (1), or not (0); and being married (1) or not (0). In our regression model we also control for zip code fixed effects, denoted by "zip code$_j$," as well as the linear and quadratic time trend, denoted by "monthly$_t$," which are the

[56] Note that each calendar month includes four full weeks and up to three more days; February (not in a leap year) is the only month that includes exactly four weeks.

linear and quadratic terms of the consecutive integers generated from all year-month pairs (January 2004–December 2010).

In the analyses of the impacts of power plant emissions we revise equation (1) to the following equation:

$$\begin{aligned} y_{i,jt} &= \gamma_0 \text{downwind emission}_{jt} + \cdots + \gamma_8 \text{downwind emission}_{j,t-8} + \\ &\quad \mathbf{x}_i' \delta + \text{zip code}_j + \text{monthly}_t + \text{error term}_{i,jt}, \end{aligned} \tag{2}$$

where the variable "downwind emission" is the previously discussed power plant emission (SO_2 or NO_x) adjusted by how downwind a New Jersey zip code is relative to the power plant (with details given in Section 3.2).

To examine the impacts of the power plant emissions on local pollution measured at each New Jersey zip code level, we use the following regression model:

$$\text{pollution}_{jt} = \phi \text{downwind emission}_{jt} + \mathbf{w}_{jt}' \pi + \text{zipcode}_j + \text{monthly}_t + \text{error term}_{jt}. \tag{3}$$

In equation (3) the variable "pollution_{jt}" denotes the previously discussed SO_2, NO_2 and $PM_{2.5}$ variables that vary monthly by each New Jersey zip code (with details given in Section 3.2). The zip code-level weather variables previously discussed (in Section 3.2) are denoted by $\mathbf{w}_{jt}$, including monthly high temperature, monthly low temperature, monthly mean temperature, monthly rainfall, and monthly snowfall.

We estimate equations (1)–(3) by ordinary least squares (OLS) with standard errors clustered at the zip code-level. Similar to our study, Currie, Neidell, and Schmieder (2009) compute standard errors clustered at the census tract-level.

Throughout our analysis we use the downwind variable together with the New Jersey zip code fixed effect. By using the zip code fixed effect, we control for the distance between each New Jersey zip code and the power plant. Because the downwind variable we constructed varies by each zip code and also by the wind direction near the power plant, once we control for the zip code fixed effects, the remaining variation of the downwind variable should come only from the latter. Thus, the inclusion of the New Jersey zip code fixed effects should allow the downwind variable to be exogenous, since the wind direction is indeed driven by nature.

4 Results

4.1 Descriptive Statistics

Table 1 reports the summary statistics about the power plant emissions and the New Jersey zip codes based on the sample of our main analysis, which includes the four New Jersey counties identified in the NJDEP's petitions—Hunterdon, Morris, Sussex, and Warren. The sample period is from January 2004 to December 2010. One important observation is that the direction-adjusted monthly SO_2 emissions (806 tons, Panel A) and NO_x emissions (92 tons, Panel A) from the power plant are much lower, on average, than the actual monthly SO_2 emissions from the power plant (2,469 tons, Panel A) and NO_x emissions (275 tons, Panel A) from the power plant.[57] This downward adjustment can be explained by the fact that New Jersey zip codes are not all perfectly downwind of the power plant. Being perfectly downwind of the power plant means that the direction toward which the wind blows is exactly equal to the direction toward which a New Jersey zip code is located relative to the power plant. Note that the average wind direction (measured on a monthly basis) near the power plant is 151.458 degrees (Panel A of Table 1), indicating that the wind blows south-southeastward. Panel A of Figure 4 further demonstrates that for the majority of our sample period the wind near the power plant blows south-southeastward (i.e., between 135 and 180 degrees regardless of the season). In comparison, Panel B of Table 1 shows that on average Sussex County is east-northeast of the power plant; Morris and Warren Counties are east-southeast

[57] Panel B of Figure 4 shows the monthly emissions of SO_2 and NO_x from the Portland Generating Station for the entire sample period.

of the power plant; and Hunterdon County is the most aligned with the wind direction near the power plant among the four counties.

Figure 5 shows that the direction-adjusted monthly SO_2 emissions from the power plant are indeed uniformly lower than the actual monthly SO_2 emissions throughout the entire sample period. Furthermore, Figure 5 shows that the downward adjustment is largest for Sussex County (Panel D), which is the county whose location is least aligned with the wind direction among the four counties; in contrast, the downward adjustment is smallest for Hunterdon County (Panel B), which is the county whose location is most aligned with the wind direction among the four counties. Consistent with Figure 5, Panel B of Table 1 shows that among the four New Jersey counties, Hunterdon is the most downwind of the power plant (with the average value of the cosine function being equal to 0.470); Morris and Warren are similarly downwind of the power plant (with the average values of the cosine function being equal to 0.335 and 0.350, respectively); and Sussex is the least downwind of the power plant (with the average value of the cosine function being equal to 0.077).

Table 2 reports the summary statistics about the birth outcomes and mothers' characteristics based on the sample of our main analysis including the four New Jersey counties (Panel A) and the full sample including all New Jersey counties (Panel B); both the estimation sample and the full sample include live singleton births only, and the sample period is from January 2004 to December 2010. Panel A shows that the proportion of full-term LBW is 1.7 percent among the four New Jersey counties; Panel B shows that the proportions of LBW and preterm births (i.e., gestational length less than 37 weeks) are 5.3 percent and 9.7 percent, respectively.

In contrast, according to the gestation and birth weight summary tables reported by the National Vital Statistics System (NVSS), the nationwide proportions of full-term LBW, LBW, and preterm births among all live singleton births during 2004–2010 (i.e., our sample period) are 2.4 percent, 6.4 percent and 10.7 percent, respectively, which are all higher than the corresponding proportions for New Jersey.[58] This pattern could be explained by a common belief that higher income is associated with better access to health care, which tends to improve birth outcomes, such as the reduction in LBW, and New Jersey is a wealthy state. According to the 2011 and 2012 American Community Survey, New Jersey has the second highest median household income (about $69,000 in 2012 inflation-adjusted dollars) in the United States, only behind the state of Maryland (about $71,000 in 2012 inflation-adjusted dollars; Noss, 2013, table 1 on p. 3).

In our birth certificate data there is no variable on household or family income. Nonetheless, in Table 2 we observe that among the four counties, Hunterdon has the highest proportion of mothers who completed a four-year college (or higher), followed in turn by Morris, Sussex and Warren. This ranking is exactly matched to the ranking of county-level median household income (2009–2013), according to the U.S. Census Bureau's statistics, with Hunterdon being the highest ($106,143), followed in turn by Morris ($98,633), Sussex ($87,335) and Warren ($70,912).[59] As a result, it could be a reasonable assumption that for our study region the proportion of mothers who completed a four-year college (or higher) is not only a control variable for the mother's educational attainment but also a proxy variable for the mother's income, because of the positive correlation suggested by Table 2 and the U.S. Census Bureau's statistics between educational attainment (information from Table 2) and income level (information from the U.S. Census Bureau's statistics).

[58] Specifically, the national level proportions of full-term LBW among live singleton births are 2.30%, 2.32%, 2.38%, 2.39%, 2.42%, 2.40%, and 2.43% for 2004–2010, respectively; the national level proportions of LBW among live singleton births are 6.30%, 6.40%, 6.48%, 6.44%, 6.40%, 6.35%, and 6.38% for 2004–2010, respectively; the national level proportions of preterm births among live singleton births are 10.66%, 10.92%, 11.03%, 10.96%, 10.62%, 10.43%, and 10.29% for 2004–2010, respectively The NVSS summary tables are available at http://205.207.175.93/Vitalstats/ReportFolders/reportFolders.aspx (accessed July 15, 2015).

[59] Detailed county-level statistics are provided at http://quickfacts.census.gov/qfd/states/ (accessed July 15, 2015).

4.2 Impacts of Being Downwind of the Power Plant on the Occurrence of Full-Term LBW

Table 3 reports the estimated impacts of being downwind of the power plant on the occurrence of full-term LBW for the sample including all four counties identified by the NJDEP's petitions and also for the sample including Hunterdon, Morris and Sussex. One important observation is that among all live singleton full-term births the impact is exclusively detected during the first month of pregnancy. Specifically, we find that being downwind of the power plant (represented by a change from zero to one in the value of the cosine function) during the first month of pregnancy, which is the eighth month prior to the birth month of a full-term (i.e., nine-month) pregnancy, could increase the likelihood of full-term LBW by approximately one percentage point. Given that the nationwide live singleton full-term LBW rate during our sample period (2004–2010) is about 2.4 percent, the finding of an increase of one percentage point could imply an approximately 42 percent increase in the occurrence of full-term LBW, one case of slow fetal growth, among live singleton births.

Because there are fetal developments unobserved to researchers and also not measured in the birth certificate data, the impacts estimated in our study are aimed to capture the effects of the interactions between maternal exposure to power plant emissions and the development of her fetus during the course of a full-term pregnancy. Our findings suggest that embryos could be most vulnerable during the early stage of pregnancy: there are no detected impacts of being downwind of the power plant during the course of a full-term pregnancy except for the first month; this finding could be explained by the possibility that fetal development during the later stage of pregnancy is able to mitigate the adverse impacts of certain *in-utero* environmental insults, but the mitigation will not be strong enough to undo those adverse impacts during the early stage of pregnancy, making an embryo (i.e., the fetus in the early stage of pregnancy) vulnerable to *in-utero* environmental insults such as maternal exposure to power plant emissions.

In Table 3 we also note that when Warren County is excluded from our estimation sample, the estimates remain very similar (columns 1–3 compared with columns 4–6), suggesting that the actual avoidance behavior of mother's relocation from Warren County to other counties is not prevalent, although this avoidance behavior is conceivable because the Portland Generating Station is located on the border between Northampton County of Pennsylvania and Warren County of New Jersey. Although we have a seven-year (i.e., 2004–2010) sample period, we lack the statistical power to conduct a separate analysis exclusively for Warren County because of the small number of full-term LBW in the sample including one county alone (i.e., Warren County).

Another important observation in Table 3 is that our estimates of the impacts of being downwind of the power plant are very similar, whether or not we control for important individual-level variables such as mother's age, education, race and ethnicity, all believed to be associated with infant birth outcomes (columns 1 vs. 2 and columns 4 vs. 5). This pattern suggests that the variations in those downwind variables are exogenous to those individual-level important covariates of infant birth outcomes, conditional on the fact that we use zip code fixed effects to control for the distance between each New Jersey zip code centroid and the power plant. The exogeneity of those downwind variables is also supported by the fact that the variations of those downwind variables come from two sources: the direction of each New Jersey zip code relative to the power plant and the wind direction near the power plant; when the former is controlled by the New Jersey zip code fixed effect, the rest of the variation of the downwind variable will be determined by the wind direction, and the wind direction being measured is indeed driven by nature and varying exogenously.

To examine the presence of important omitted variables that vary monthly and also by each zip code, we conduct a falsification check by adding a term of being downwind of the power plant during the month after the childbirth, that is, a "leading" term. If our finding is actually driven by certain zip code-level unobserved variables that vary monthly, then this leading term can be a proxy of those unobserved variables and its coefficient can be statistically significant if those unobserved variables do have impacts on the occurrence of full-term LBW. In columns (3) and (6) of Table 3 we see that the coefficient of that leading term is not statistically significant, suggesting that the zip code-level unobserved variables that vary monthly have little impact on the occurrence of full-term LBW; furthermore, the estimate of that coefficient is close to zero, which is also consistent with the fact that there is no impact on the occurrence of full-term LBW from being downwind of the power plant during the month after childbirth.

To check the robustness of our estimates, we use two additional samples including all zip codes that are 40 miles and 35 miles of the power plant, respectively.[60] The results of our robustness checks are reported in Table 4 with two important observations. First, the estimates reported in Table 4 are fully consistent with the estimates reported in Table 3. By focusing on the zip codes that are close to the power plant, we confirm the same pattern as what we find by using the four counties identified by the NJDEP's petitions—Hunterdon, Morris, Sussex and Warren. Second, because most of the zip codes of the four counties are within 35 miles of the power plant, the estimates (columns 4–6 of Table 4) obtained from the 35-mile sample are similar to those reported in Table 3: being downwind of the power plant during the first month of pregnancy could increase the likelihood of full-term LBW by approximately one percentage point. Furthermore, we note that the magnitude of this estimate becomes smaller and it decreases to 0.6 percentage points (columns 1–3) when we use the 40-mile sample, which includes counties (i.e., Mercer, Middlesex, Passaic, Somerset and Union) that are actually not identified by the NJDEP's petitions as the impacted area of the Portland Generating Station.

Overall, the findings reported in Table 4 are consistent with the NJDEP's petitions that Hunterdon, Morris, Sussex and Warren Counties are impacted by the Portland Generating Station, and the impact on full-term LBW from being downwind of the power plant can be increasing (or decreasing) as the distance between the power plant and the mother's residence decreases (or increases). Indeed, the impact is not found in the area that is far away from the

[60] The New Jersey counties included in the 40-mile and 35-mile samples and the associated summary statistics are reported in Appendix Table 1.

power plant. Specifically, Table 5 shows that no impact is found in these three counties—Cape May, Hudson and Salem (with their locations shown on Figure 3) that are far away from the power plant and also not directly downwind of the power plant. In addition, in the sample including New Jersey zip codes that are at least 80 miles away from the power plant we find no impact on the occurrence of full-term LBW from being downwind of the power plant. Note that the numbers of observations of the three-county sample (56,054, column 1 of Table 5) and the 80-mile sample (67,573, column 2 of Table 5) are all greater than the numbers of observations of the 35-mile sample (48,997, columns 4–6 of Table 4) and the four-county sample (51,809, columns 1–3 of Table 3), so the statistically insignificant effects reported in Table 5 are not the results from having smaller samples but rather likely to be the results from mothers' living far away from the power plant.

To further check the potential bias (in our estimated health impacts of the power plant emissions) from omitting important variables that vary monthly and also by each zip code, we conduct falsification checks on the 35-mile and the 40-mile samples by including leading terms of the downwind variable, that is, being downwind of the power plant during the sixth month after birth, till during the 12th month after birth. The results of the falsification checks are reported in Table 6: none of the coefficients of those leading terms are statistically significant, which is fully consistent with the null hypothesis known to be true that there is no impact of being downwind of the power plant during the period of six months to one year after birth on the infant health at birth. Overall, the results in Tables 5 and 6 suggest that the impacts on slow fetal growth (indicated by full-term LBW) shown in Tables 3 and 4 stem from the Portland Generating Station and the proximity to that power plant, rather than the effects of unmeasured determinants of fetal development that vary monthly and also by each zip code.

4.3 Impacts of Power Plant Emissions on the Occurrence of Full-Term LBW

We further examine whether the impacts on full-term LBW are indeed the results of maternal exposure to the emissions from the Portland Generating Station during pregnancy. We report the results in Tables 7 and 8 for the SO_2 emissions and the NO_x emissions from the power plant, respectively.

In Table 7 we observe the same pattern as the ones shown in Tables 3–5: the impacts on full-term LBW from maternal exposure to the SO_2 emissions from the Portland Generating Station are exclusively detected for the first month of pregnancy among live singleton full-term births (columns 1–6). Based on the sample including Hunterdon, Morris and Sussex, the three counties that are not adjacent to the Portland Generating Station, we find that when the direction in which a zip code is located from the power plant is the same as the direction toward which the wind blows near the power plant, an increase of 1,000 tons of SO_2 emissions (which is about 3 percent of the power plant's annual total SO_2 emission) from the power plant during the first month of pregnancy could increase the likelihood of full-term LBW by approximately 0.24 percentage points among live singleton full-term births (columns 1–2). Based on the national level live singleton full-term LBW rate during our sample period (2004–2010), which is 2.4 percent, this finding of an increase of 0.24 percentage point could imply an approximately 10 percent increase in the occurrence of live singleton full-term LBW. This estimate increases slightly to 0.25 percentage points (or 10.42 percent) when we keep only Hunterdon and Morris Counties in the sample (columns 3–4), which is consistent with the fact that, compared with Sussex County, Hunterdon and Morris Counties are located in an area more aligned with the direction toward which the wind near the power plant blows, and therefore the estimated impact could be greater for the area more downwind of the power plant once the distance to the power plant is controlled by using the zip code fixed effects. In addition, we find that the estimate decreases to 0.17 percentage points (or 7.08 percent) when we include all zip codes that are 40 miles of the power plant (column 5–6), which could be explained by the fact the 40-mile sample includes counties that are actually not identified in the NJDEP's petitions (i.e., Mercer, Middlesex, Passaic, Somerset and Union). Furthermore, when the sample includes only Cape May, Hudson and Salem, the three counties that are far away from the power plant and also located in an area not directly downwind of the power plant, we find no impact on full-term LBW from being exposed to SO_2 emissions from the power plant (column 7).

In contrast to SO_2 emissions, in Table 8 we find no statistically significant impact on the occurrence of full-term LBW from maternal exposure to the power plant's NO_x emissions in each of the cases (with the same number of observations) examined in Table 7. This finding, however, is consistent with the Portland Rule, which exclusively identified that it is SO_2 emitted from the Portland Generating Station that has reached the downwind state, New Jersey. One possible reason for this finding is that two processes—reaction with the hydroxyl radical (OH) and dry deposition, either of which can remove SO_2 and NO_x from the atmosphere and therefore terminate their lifetime, are preventing less SO_2, but more NO_x, emitted from the power plant from affecting the downwind region.[61]

We further investigate the transportability of SO_2 and NO_x emissions from the power plant by examining the pollution level measured at each New Jersey zip code based on the EPA's AQS data. The results are reported in Table 9.[62] Consistent with the Portland Rule, Panel A shows that, on a monthly basis, SO_2 levels measured at zip codes that are within 40 miles of the power plant could increase by approximately 1.587 ppb as a result of the increase of 1,000 tons of SO_2 emissions from the power plant, when the direction in which a zip code is located from the power plant is the same as the direction toward which the

[61] Longer lifetime of these gases will allow them to be transported in the atmosphere farther away from their origin. For instance, the lifetime of SO_2, based on the reaction with OH (at a typical atmospheric level of OH), is about one week; it is much longer than that of NO_2 (one case of NO_x), which is about one day (Seinfeld and Pandis, 1998, p. 259 and p. 314). The average dry deposition velocities above land for SO_2 and NO_2 are about 0.8 and 0.02 centimeters per second, respectively (Möller, 2010, p. 448). When both processes considered, the lifetime of SO_2 can be two days, but the lifetime of NO_2 can be one day only.

[62] In Appendix Table 3 we report the results of our robustness check, where we use a 15-mile radius for the construction of pollution and weather variables. The results in Appendix Table 3 are similar to those in Table 9.

wind blows near the plant (column 4). When we include two or three of the four New Jersey counties identified in the NJDEP's petitions, the estimate increases to 1.664 ppb (column 2) or 1.752 ppb (column 3), and the estimate of the impact becomes the greatest (2.249 ppb in column 1) when only Warren County is included in the sample, which is consistent with the fact that the Portland Generating Station is immediately next to Warren County. In contrast, we find that among the zip codes that are at least 80 miles away from the power plant, the estimate of the SO_2 pollution impact is statistically insignificant and also close to zero (column 5); this result is consistent with the previous findings that no impact on the occurrence of full-term LBW from being downwind of the power plant is found in the sample including zip codes that are at least 80 miles away from the power plant.

In Panel B we also find an increase in the $PM_{2.5}$ level in the area including the four New Jersey counties (columns 1–4), as a result of the SO_2 emissions from the power plant, but we do not find this impact in the area that is far away (i.e., at least 80 miles) from the power plant (column 5). These findings are similar to the ones reported in Panel A. The reason why $PM_{2.5}$ levels in a downwind region can be affected by the power plant's SO_2 emissions is that SO_2 contributes to the formation of sulfates, which can be transported in the atmosphere through prevailing wind and then become an ingredient of fine particle pollution in the region downwind of the power plant (Schneider and Bank, 2010). In contrast, Panel C shows that NO_x emitted from the power plant appears to be able to reach Warren County only (the county immediately next to the power plant), which could be the result of the aforementioned two atmospheric processes (i.e., reaction with the hydroxyl radical and dry deposition) of this geographic region.

Taken together, Panels A, B and C of Table 9 suggest that the increases in the SO_2 and $PM_{2.5}$ levels measured at the zip code level in the downwind region could be the reason for the previous findings that being downwind of the power plant and in particular, being exposed to the power plant's SO_2 emissions during the first month of pregnancy could increase the likelihood of slow fetal growth, which is indicated by the occurrence of full-term LBW.

One drawback of our study is that we have the information on which zip code the mother resides in, but we do not have the information on the scope of the mother's daily activities. It is possible that the mother spends most of her day at work, especially during the early stage of pregnancy, and the workplace is in a zip code that is far away from her residential zip code. As a result, our measures of being downwind of the power plant and being exposed to the power plant's emissions are for potential exposure only, which can be substantially different from the mother's actual exposure to the power plant's emissions.

To assess the impact of this measurement error, we check the power plant's hourly emission data provided by the EPA's AMPD. The results are reported in Figure 6, where we find that the power plant's SO_2 emissions were consistently peaked around 3:00 PM during our sample period (2004–2010). The monthly average speed of the wind measured near the power plant during our sample period is about 6.7 miles per hour (mph). Panel B of Table 1 shows that the average distance between the mother's residential zip code and the power plant is 12.574 miles for Warren, 25.483 miles for Hunterdon, 26.017 miles for Sussex, and 31.117 miles for Morris. So, the travel time for SO_2 emitted from the power plant to reach the four counties could be between two and five hours, based on the 6.7 mph wind speed. Thus, it is possible for the SO_2 emissions that are peaked at 3:00 PM to reach the four counties between 5:00 PM and 8:00 PM, at the time when workers usually return home from work. According to the U.S. Census Bureau, during 2009–2013 the average travel time for workers of age 16 and over is 33.6 minutes for Hunterdon, 30.0 minutes for Morris, 37.7 minutes for Sussex, and 34.4 minutes for Warren (all close to the New Jersey average of 30.4 minutes, which is higher than the national average of 25.5 minutes).[63] Hence, even though the mothers from the four counties can spend most of the daytime at work, away from their homes, they still can be exposed to elevated pollution levels measured at their residential zip codes, because of the power plant's emissions that are peaked in the afternoons. Therefore, in our empirical setting the variables of being downwind of the power plant and being exposed to

[63] These summary statistics are available at http://quickfacts.census.gov/qfd/states/ (accessed July 15, 2015).

the power plant's emissions, all measured at the mothers' residential zip codes, can still be meaningful for capturing a portion of the mothers' actual pollution exposure that is affected by the power plant's emissions

5 Discussion

Our finding suggests that maternal exposure to power plant emissions during early pregnancy may be most consequential for fetal development. Specifically, we find that the consequence of prenatal exposure to power plant emissions of SO_2 (a major precursor to ambient $PM_{2.5}$ concentrations) on the occurrence of LBW among live singleton full-term births is significantly impactful during the first month of pregnancy, which adds more evidence in support of several association-based studies by Dejmek et al. (1999), Dugandzic et al. (2006), Liu et al. (2003) and Mohorovic (2004). In particular, Dejmek et al. (1999) find that among live singleton full-term births of European origin, IUGR is significantly correlated with prenatal exposure to $PM_{2.5}$ (and also PM_{10}) during the first month of pregnancy. Dugandzic et al. (2006) find a significant association between SO_2 exposure in the highest quartile during the first trimester and the risk of LBW among live singleton full-term births in Canada. Similarly, also based on pregnancy outcomes in Canada, Liu et al. (2003) find that SO_2 exposure during the first month of pregnancy is significantly associated with LBW among live singleton full-term births. Using data from Croatia, Mohorovic (2004) find that greater exposure to SO_2 during the first two months of pregnancy is associated with not only lower birth weight but also shorter gestational length.

Our finding also suggests that *in-utero* exposure to SO_2 and $PM_{2.5}$ due to coal-fired power plant emissions could induce fetal growth restrictions, of which the exact biological mechanism is still being examined in the medical and environmental health fields. Among several potential pathways proposed in the literature, such as inflammation, changes in blood coagulability and viscosity, endothelial function and hemodynamic responses (Kannan et al., 2006; Slama et al., 2008), there is growing evidence showing that intrauterine oxidative stress is highly correlated with the occurrence of IUGR (Al-Gubory, Fowler and Garrel 2010; Kannan et al., 2006). Inhaled fine particles can contain many free radicals, which include reactive oxygen species (ROS), reactive nitrogen species, and reactive sulfur species (RSS). One important response to oxidative stress is the influx of inflammatory cells to the sites of damage. Inflammatory cells can generate and release more free radicals, which will initiate another round of oxidative stress. Moreover, maternal inflammation could be associated with inadequate placental perfusion that restricts fetal growth due to interference of transplacental oxygen and nutrient transport (Kannan et al., 2006). Inflammation could also affect maternal host's immune system that increases maternal risk of infections, which in turn could influence maternal nutrition supply or disturb transplacental nutrient exchanges or cause fetal infection that impairs fetal growth and development. While the ROS-induced oxidative stress and its adverse impact on fetal growth have been extensively studied in the medical field (Al-Gubory, Fowler and Garrel 2010; Kannan et al., 2006), the RSS-induced oxidative stress has become an emerging concept (Giles and Jacob, 2002; Mohorovic, 2004). Usually, sulfur is considered as part of cellular antioxidant system, which will reduce oxidative stress; however, there is more evidence showing that RSS can actually have stressor properties that are similar to ROS, inducing oxidative stress (Giles and Jacob, 2002; Mohorovic, 2004). Our finding suggests that the adverse impact on fetal growth could arise from possibly RSS-induced intrauterine oxidative stress due to Portland Generating Station's emissions of SO_2 (a major precursor to ambient $PM_{2.5}$ concentrations) travelling to the downwind region of New Jersey.

Previous studies have suggested that when facing a compromised *in-utero* environment, male and female fetuses will respond differently, and therefore they can exhibit sexually dimorphic birth outcomes. However, sex-specific effects of prenatal exposure to air pollution on fetal growth have not received much attention in the epidemiological literature. Existing studies that have examined sex-specific effects, reviewed in Ghosh et al. (2007), suggest a stronger effect of pollution exposure (e.g., SO_2, $PM_{2.5}$, CO, O_3, and NO_2) on low birth weight or very low birth weight for males than for females.

Indeed, in Table 10 we find that the impacts of being downwind of the power plant during the first month of pregnancy on the occurrence of slow fetal growth are salient among males, but on average there is no effect detected among females; the magnitudes of the estimate among males (between 1.2 and 1.3 percentage points, reported in Table 10) are slightly greater than the magnitudes of the estimate (approximately 1 percentage point, reported in Table 3) when both sexes are included in the estimation sample. This pattern suggests that the adverse impact of maternal exposure to power plant emissions during the early stage of pregnancy could concentrate among male fetuses. Our results indicate that male fetuses can be more vulnerable than female fetuses to *in-utero* environmental insults (such as power plant pollutions) during the early stage of pregnancy, and the adverse impacts during the first month of pregnancy may not be overcome by the catch-up growth of male fetuses during the later stage of pregnancy, such as the fetal growth spurt starting at the end of the second semester or the beginning of the third trimester.

The findings of our study are consistent with the sex difference predicted by the theory of Developmental Origins of Health and Disease (Aiken and Ozanne, 2013). Our results also provide evidence supporting a contention that "boys live dangerously in the womb" (Eriksson et al., 2010). Unless otherwise stated, the following discussions on sex-specific response to *in-utero* insults are based on Aiken and Ozanne (2013), Clifton (2010), Eriksson et al. (2010), and Renzo et al. (2007).

Starting from the early stage of human development, males tend to grow faster at every gestation age. To sustain their fast growth, males also invest less in placental growth. Prior to the 10th week of pregnancy (a period when most of organs are forming), male embryos experience more rapid cell divisions, and more frequent cell cycles can expose male embryos to a higher risk of effective *in-utero* insults. After the 10th week of pregnancy, male fetuses continue to grow faster but mature more slowly than female fetuses. The greater growth velocity, which demands more nutrition and oxygen but with less mature organs and systems, potentially can make males more susceptible to *in-utero* environmental insults.

More importantly, when facing an *in-utero* insult that restricts nutrition and oxygen supply, females tend to perform a higher level of epigenetic modifications and changes of mRNA and protein expressions, to reduce their growth rates and adapt placenta to the compromised *in-utero* environment. This developmental adaptation potentially explains why we do not detect any statistically significant effect (on average) of maternal exposure to power plant emissions during pregnancy on the full-term LBW (columns 2, 4 and 6 of Table 10) among females. In contrast, male fetuses lack the same level of "plasticity" that female fetuses have, which will expose male fetuses to greater risks of becoming undernourished. In other words, when resource constraints change, female fetuses can remaximize the usage of intrauterine environment to achieve their optimal outcomes under the new constraints, and the new optimal outcomes can lead to minor reductions in fetal growth, thus avoiding IUGR; in contrast, when facing more constrained resources, male fetuses can continue to develop without recognizing the new constraints and in the end fail to sustain their growth and development or fail to have any capacity to mitigate the *in-utero* environmental insults.

Interestingly, our results suggest that the first month of pregnancy could have a crucial impact on male fetuses' growth if fetuses are carried to full terms. It is possible that male fetuses' organs and placenta are not developed to the level of adjusting male fetuses to a compromised *in-utero* environment during the early stage of pregnancy, and when maternal exposure to pollution persists, growth of male fetuses will eventually be restricted.

6 Conclusion

The Portland Rule provides us with a rare opportunity to examine the impacts of coal-fired power plant emissions on infant health at birth: the impact area was scientifically verified and the sole source of the air pollution in the downwind region was exactly identified by the

NJDEP and also by the EPA independently. Our study assembled a set of evidence showing the infant health impacts from coal-fired power plant emissions, such as sulfur dioxide, which can contribute to the formation of sulfates in the atmosphere—a dominate ingredient of fine particle pollution east of Mississippi of the United States (Schneider and Bank, 2010): infant birth outcomes could be adversely affected by the Portland Generating Station, a large polluter identified in the Portland Rule, and the impact region can be 20 to 40 miles far away from the power plant due to prevailing winds.

Specifically, among all live singleton births during 2004–2010 we find that for mothers who live in the impact area identified in the Portland Rule, being downwind of the power plant during the first month of pregnancy can increase the likelihood of full-term LBW, an indicator of slow fetal growth, by approximately one percentage point, which is an increase of approximate 42 percent since the national average rate of live singleton full-term LBW is about 2.4 percent during our sample period. In contrast, no effect of being downwind of the power plant on slow fetal growth (represented by full-term LBW) is found in the area far away from the power plant: for instance, the area that is at least 80 miles away from the power plant, or the counties that are far away and also not directly downwind of the power plant.

Using data on the power plant's emissions adjusted by how downwind a New Jersey zip code is relative to the power plant, we find that the health impacts of the direction-adjusted power plant emissions are fully consistent with the findings on the health impacts of being downwind of the power plant: maternal exposure to an increase of 1,000 tons of SO_2 emissions from the power plant (roughly three percent of the power plant's annual total SO_2 emissions) in a perfectly upwind direction during the first month pregnancy could increase the likelihood of full-term LBW by about 0.24 percentage points, or 10 percent (when compared with the national level live singleton full-term births during our sample period) in the area that is 20 to 40 miles away but downwind of the power plant, which includes the Hunterdon, Morris, and Sussex Counties of New Jersey. Furthermore, we provide evidence that is consistent with the Portland Rule, suggesting that it is SO_2 and $PM_{2.5}$, not NO_x (whose emissions are reported in the EPA's AMPD in addition to SO_2 emissions), that have the potential to travel long distance in the air through prevailing winds.

Adding to the scientific findings presented in the Portland Rule, our results suggest an impact of *in-utero* exposure to SO_2 and $PM_{2.5}$ during the first month of pregnancy (i.e., during the embryo stage) on the occurrence of slow fetal growth, indicated by the full-term LBW. This finding echoes the results of several studies pinpointing the critical gestation period for adverse impacts on infant health from *in-utero* environmental insults (such as prenatal exposure to air pollution). To the best of our knowledge, we also provide the first evidence in the economics field regarding the adverse impact on fetal growth from possibly reactive sulfur species-induced intrauterine oxidative stress, arising from maternal exposure to emissions of SO_2 (a major precursor to ambient $PM_{2.5}$ concentrations), whose travelling from the emission source to the downwind region has been confirmed in the Portland Rule. Furthermore, we find suggestive evidence in support of the theory of Developmental Origins of Health and Disease (Aiken and Ozanne, 2013): male fetuses can be more vulnerable than female fetuses to *in-utero* environmental insults during the early stage of pregnancy, and the adverse impacts during the early stage of pregnancy may not be countervailed by the growth spurts of male fetuses during the later stage of pregnancy.

Our research design is guided by two aspects of the Portland Rule: first, it provides scientific evidence on the travel distance and direction of SO_2 emitted from the Portland Generating Station, which is about 40 miles downwind of the power plant; second, it shows that the power plant is an independent source of air pollution and a significant contributor to the violation of NAAQS in the downwind region. By focusing on the impact area identified in the Portland Rule, we are able to exploit the variation in the power plant emissions that can be independent of local pollution sources. By focusing on those mothers who live in the Hunterdon, Morris and Sussex Counties of New Jersey, the area that is 20 to 40 miles away from the power plant, we aim to preclude possible presence of protection behaviors of those who live in close proximity to the power plant, as well as selective migration away from the power plant. Furthermore, we focus on the period (2004–2010) that is prior to the date of the Portland Rule, during which residents living 20 to 40 miles away but downwind of the power plant may not have been aware of the impacts of the power plant, and thus the possibility of their selective migration away from the power plant can be minimal.

However, the focal region of our study is a wealthy part of New Jersey, which is a wealthy state. Thus, our findings on the adverse infant health impacts of the power plant emissions can be an under-estimation compared with the actual impacts for a general population, since higher income can be associated with better access to health care, which usually prevents the occurrence of adverse infant health outcomes. Besides, to have infant birth weight information, we rely on the birth certificate data, from which we only observe infant weights of live births. As a result, our study will incur a bias from "fetal selection" (Currie, 2009) or "selective mortality" (Almond and Currie, 2011): we are likely to have under-estimated the actual infant health impacts of power plant emissions by using a sample of survivors of *in-utero* environmental insults. Nonetheless, in the evaluation of adverse impacts of power plant emissions, an under-estimation may still be informative to policy-makers, when a potential lower bound of the actual adverse impact is considered.

The Portland Rule is precedent-setting and it is expected to encourage more petitions from the downwind states against upwind polluters. The ruling by the Third Circuit in the *GenOn REMA LLC v. EPA* case affirmed EPA's proper use of the AERMOD for air quality impact analysis, which also has precedential impact because the court's ruling essentially allows the EPA to continue using its own air quality impact modeling to identify individual upwind polluters causing downwind NAAQS violations and hold those upwind polluters accountable. In this regard, our study is aimed at broadening the scope of cross-border pollution analysis by taking into account adverse infant heath impacts from upwind polluters, which can burden the downwind states disproportionately.

References

Aiken, C. E. and S. E. Ozanne (2013). "Sex Differences in Developmental Programming Models." *Reproduction* 145 (1): R1–R13.

Al-Gubory, K. H., P. A. Fowler and C. Garrel (2010). "The Roles of Cellular Reactive Oxygen Species, Oxidative Stress and Antioxidants in Pregnancy Outcomes." *International Journal of Biochemistry & Cell Biology* 42 (10): 1634–1650.

Almond, D., K. Y. Chay and D. S. Lee (2005). "The Costs of Low Birth Weight." *Quarterly Journal of Economics* 120 (3): 1031–1083.

Almond, D. and J. Currie (2011). "Killing Me Softly: The Fetal Origins Hypothesis." *Journal of Economic Perspectives* 25 (3): 153–172.

Barker, D. J. P. (1995). "Fetal Origins of Coronary Heart Disease." *BMJ: British Medical Journal* 311 (6998): 171–174.

Behrman, J. R. and M. R. Rosenzweig (2004). "Returns to Birthweight." *Review of Economics and Statistics* 86 (2): 586–601.

Behrman, J. R., M. R. Rosenzweig and P. Taubman (1994). "Endowments and the Allocation of Schooling in the Family and in the Marriage Market: The Twins Experiment." *Journal of Political Economy* 102 (6): 1131–1174.

Brooks, A.-M., R. S. Byrd, M. Weitzman, P. Auinger and J. T. McBride (2001). "Impact of Low Birth Weight on Early Childhood Asthma in the United States." *Archives of Pediatrics & Adolescent Medicine* 155 (3): 401–406.

Caudri, D., A. Wijga, U. Gehring, H. A. Smit, B. Brunekreef, M. Kerkhof, M. Hoekstra, J. Gerritsen and J. C. de Jongste (2007). "Respiratory Symptoms in the First 7 Years of Life and Birth Weight at Term." *American Journal of Respiratory and Critical Care Medicine* 175 (10): 1078–1085.

Clifton, V. L. (2010). "Review: Sex and the Human Placenta: Mediating Differential Strategies of Fetal Growth and Survival." *Placenta* 31 (Supplement): S33–S39.

Currie, J. (2009). "Healthy, Wealthy, and Wise: Socioeconomic Status, Poor Health in Childhood, and Human Capital Development." *Journal of Economic Literature* 47 (1): 87–122.

Currie, J. (2011). "Inequality at Birth: Some Causes and Consequences." *American Economic Review: Papers & Proceedings* 101 (3): 1–22.

Currie, J., L. Davis, M. Greenstone and R. Walker (2015). "Environmental Health Risks and Housing Values: Evidence from 1,600 Toxic Plant Openings and Closings." *American Economic Review* 105 (2): 678–709.

Currie, J. and R. Hyson (1999). "Is the Impact of Health Shocks Cushioned by Socioeconomic Status? The Case of Low Birthweight." *Papers and Proceedings of the One Hundred Eleventh Annual Meeting of the American Economic Association* (May, 1999) 89 (2): 245–250.

Currie, J. and M. Neidell (2005). "Air Pollution and Infant Health: What Can We Learn from California's Recent Experience?" *Quarterly Journal of Economics* 120 (3): 1003–1030.

Currie, J., M. Neidell and J. F. Schmieder (2009). "Air Pollution and Infant Health: Lessons from New Jersey." *Journal of Health Economics* 28 (3): 688–703.

Currie, J. and R. Walker (2011). "Traffic Congestion and Infant Health: Evidence from E-ZPass." *American Economic Journal: Applied Economics* 3 (1): 65–90.

Dejmek, J., S. G. Selevan, I. Beneš, I. Solanský and R. J. Šrám (1999). "Fetal Growth and Maternal Exposure to Particulate Matter during Pregnancy." *Environmental Health Perspectives* 107 (6): 475–480.

Dugandzic, R., L. Dodds, D. Stieb and M. Smith-Doiron (2006). "The Association between Low Level Exposures to Ambient Air Pollution and Term Low Birth Weight: A Retrospective Cohort Study." *Environmental Health* 5: 3.

Environmental Integrity Project (EIP) (2007). "Dirty Kilowatts: America's Most Polluting Power Plants." July 2007 Report. Washington D.C.: Environmental Integrity Project, available at http://www.dirtykilowatts.org/Dirty_Kilowatts2007.pdf (accessed July 15, 2015).

Environmental Protection Agency (EPA) (2011). "Final Response to Petition From New Jersey Regarding SO_2 Emissions From the Portland Generating Station." *Federal Register* 76 (215) (Monday, November 7, 2011/Rules and Regulations): 69052–69077.

Eriksson, J. G., E. Kajantie, C. Osmond, K. Thornburg and D. J. P. Barker (2010). "Boys Live Dangerously in the Womb." *American Journal of Human Biology* 22 (3): 330–335.

Ghosh, R., J. Rankin, T. Pless-Mulloli and S. Glinianaia (2007). "Does the Effect of Air Pollution on Pregnancy Outcomes Differ by Gender? A Systematic Review." *Environmental Research* 105 (3): 400–408.

Giles, G. I. and C. Jacob (2002). "Reactive Sulfur Species: An Emerging Concept in Oxidative Stress." *Biological Chemistry* 383 (3-4): 375.

Goldenberg, R. L. and S. P. Cliver (1997). "Small for Gestational Age and Intrauterine Growth Restriction: Definitions and Standards." *Clinical Obstetrics and Gynecology* 40 (4): 704–714.

Goldenberg, R. L. and J. F. Culhane (2007). "Low Birth Weight in the United States." *American Journal of Clinical Nutrition* 85 (2): 584S–590S.

Hales, C. N. and D. J. P. Barker (2001). "The Thrifty Phenotype Hypothesis: Type 2 Diabetes." *British Medical Bulletin* 60 (1): 5–20.

Kannan, S., D. P. Misra, J. T. Dvonch and A. Krishnakumar (2006). "Exposures to Airborne Particulate Matter and Adverse Perinatal Outcomes: A Biologically Plausible Mechanistic Framework for Exploring Potential Effect Modification by Nutrition." *Environmental Health Perspectives* 114 (11): 1636–1642.

Lin, C.-M., C.-Y. Li, G.-Y. Yang and I. F. Mao (2004). "Association between Maternal Exposure to Elevated Ambient Sulfur Dioxide during Pregnancy and Term Low Birth Weight." *Environmental Research* 96 (1): 41–50.

Liu, S., D. Krewski, Y. Shi, Y. Chen and R. T. Burnett (2003). "Association between Gaseous Ambient Air Pollutants and Adverse Pregnancy Outcomes in Vancouver, Canada." *Environmental Health Perspectives* 111 (14): 1773–1778.

Luechinger, S. (2014). "Air Pollution and Infant Mortality: A Natural Experiment from Power Plant Desulfurization." *Journal of Health Economics* 37: 219–231.

Maisonet, M., T. J. Bush, A. Correa and J. J. K. Jaakkola (2001). "Relation between Ambient Air Pollution and Low Birth Weight in the Northeastern United States." *Environmental Health Perspectives* 109 (Supplement 3): 351–356.

Maisonet, M., A. Correa, D. Misra and J. J. K. Jaakkola (2004). "A Review of the Literature on the Effects of Ambient Air Pollution on Fetal Growth." *Environmental Research* 95 (1): 106–115.

Möller, D. (2010). *Chemistry of the Climate System.* Berlin, DEU: Walter de Gruyter.

Mohorovic, L. (2004). "First Two Months of Pregnancy—Critical Time for Preterm Delivery and Low Birthweight Caused by Adverse Effects of Coal Combustion Toxics." *Early Human Development* 80 (2): 115–123.

Nelson, K. B. and J. K. Grether (1997). "Cerebral Palsy in Low-Birthweight Infants: Etiology and Strategies for Prevention." *Mental Retardation and Developmental Disabilities Research Reviews* 3 (2): 112–117.

New Jersey Department of Environmental Protection (NJDEP) (2010 a). Petitions Pursuant to Section 126 of the Clean Air Act: Unlawful Transport of Emissions from the Coal-fired Portland Generating Station ("Portland Plant" or "Portland") to New Jersey, May 12, 2010 Petition (Initial), State of New Jersey, available at http://www.state.nj.us/dep/baqp/petition/126complete.pdf (accessed July 15, 2015).

New Jersey Department of Environmental Protection (NJDEP) (2010 b). Petitions Pursuant to Section 126 of the Clean Air Act: Unlawful Transport of Emissions from the Coal-fired Portland Generating Station ("Portland Plant" or "Portland") to New Jersey, September 13, 2010 Supplemental Petition, State of New Jersey, available at http://www.state.nj.us/dep/baqp/petition/Complete126-suppltr.pdf (accessed July 15, 2015).

Noss, A. (2013). "Household Income: 2012." American Community Survey Briefs, September 2013, U.S. Department of Commerce, Economics and Statistics Administration, U.S. Census Bureau, available at http://www.census.gov/prod/2013pubs/acsbr12-02.pdf (accessed July 15, 2015).

Renzo, G. C. D., A. Rosati, R. D. Sarti, L. Cruciani and A. M. Cutuli (2007). "Does Fetal Sex Affect Pregnancy Outcome?" *Gender Medicine* 4 (1): 19–30.

Ritz, B. and M. Wilhelm (2008). "Air Pollution Impacts on Infants and Children. Southern California Environmental Report Card – Fall 2008." Report. Los Angeles, CA: UCLA Institute of the Environment and Sustainability, available at http://www.environment.ucla.edu/reportcard/article1700.html (accessed July 15, 2015).

Schneider, C. and J. Bank (2010). "The Toll from Coal: An Updated Assessment of Death and Disease from America's Dirtiest Energy Source." Report. Boston, MA: Clean Air Task

Force, available at http://www.catf.us/resources/publications/files/The_Toll_from_Coal.pdf (accessed July 15, 2015).

Seinfeld J. H. and S. N. Pandis (1998). *Atmospheric Chemistry and Physics, from Air Pollution to Climate Change*. John Wiley & Sons, Inc.

Selevan, S. G., C. A. Kimmel and P. Mendola (2000). "Identifying Critical Windows of Exposure for Children's Health." *Environmental Health Perspectives* 108 (Supplement 3): 451–455.

Slama, R., L. Darrow, J. Parker, T. J. Woodruff, M. Strickland, M. Nieuwenhuijsen, S. Glinianaia, K. J. Hoggatt, S. Kannan, F. Hurley, J. Kalinka, R. Šrám, M. Brauer, M. Wilhelm, J. Heinrich, and B. Ritz. (2008). "Meeting Report: Atmospheric Pollution and Human Reproduction." *Environmental Health Perspectives* 116 (6): 791–798.

United States Court of Appeals for the Third Circuit (Opinion Filed: July 12, 2013). No. 12–1022. GenOn REMA, LLC, Petitioner v. United States Environmental Protection Agency, Respondent. On Petition for Review of Final Agency Action of the United States Environmental Protection Agency (EPA-HQ-OAR-2011-0081), available at http://www2.ca3.uscourts.gov/opinarch/121022p.pdf (accessed July 15, 2015).

Wang, X., H. Ding, L. Ryan, X. Xu, X. Wang, H. Ding, L. Ryan and X. Xu (1997). "Association between Air Pollution and Low Birth Weight: A Community-Based Study." *Environmental Health Perspectives* 105 (5): 514–520.

Wilcox, A. J. (2001). "On the Importance—and the Unimportance—of Birthweight." *International Journal of Epidemiology* 30 (6): 1233–1241.

Wiles, N. J., T. J. Peters, D. A. Leon and G. Lewis (2005). "Birth Weight and Psychological Distress at Age 45-51 Years: Results from the Aberdeen Children of the 1950s Cohort Study." *British Journal of Psychiatry* 187 (1): 21–28.

Yoshida, S., N. Unno, H. Kagawa, N. Shinozuka, S. Kozuma and Y. Taketani (2000). "Prenatal Detection of a High-Risk Group for Intrauterine Growth Restriction Based on Sonographic Fetal Biometry." *International Journal of Gynecology & Obstetrics* 68 (3): 225–232.

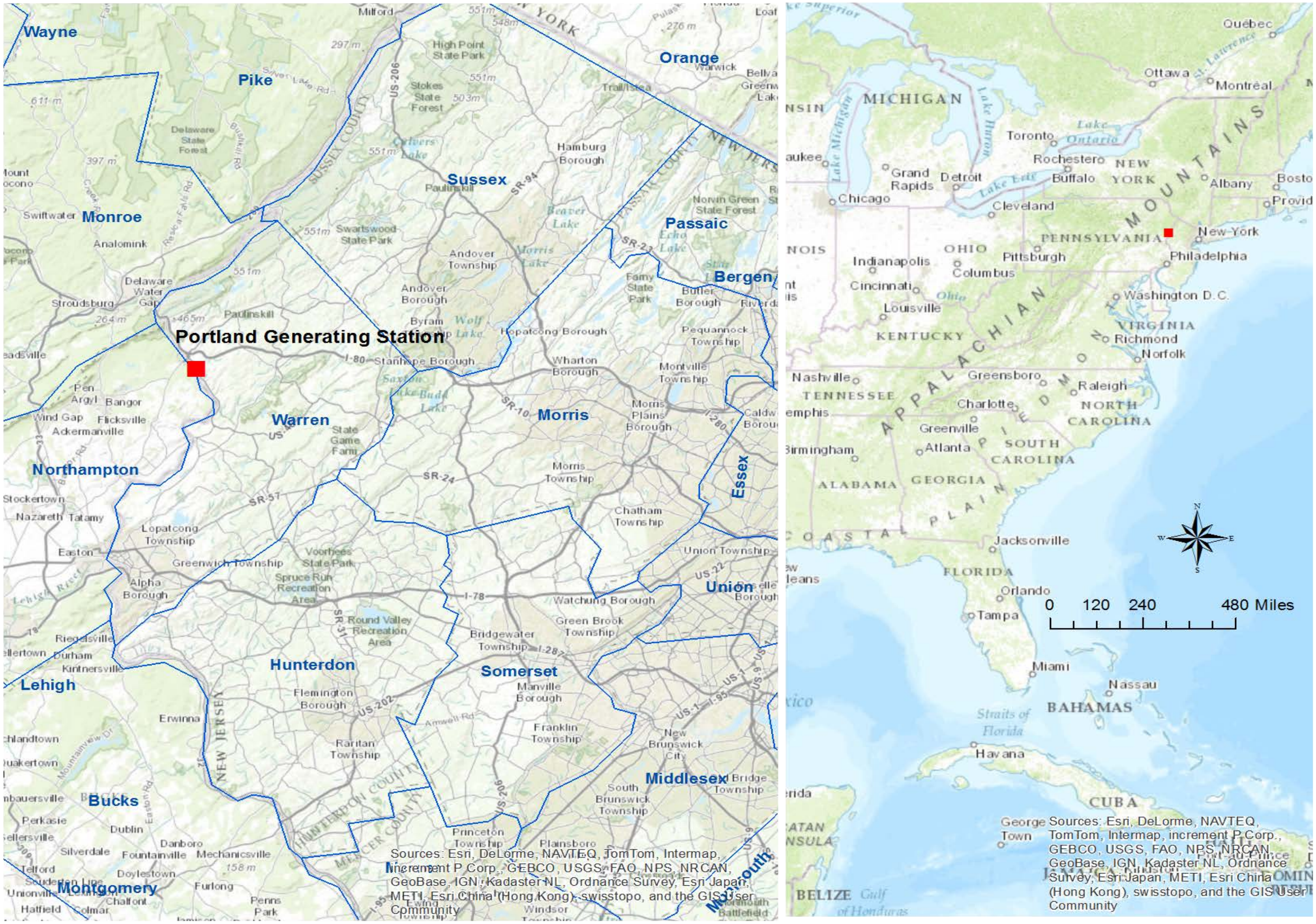

Figure 1: Location of the Portland Generating Station

Note: The address of the Portland Generating Station is 40897 River Road, Portland, PA 18351.

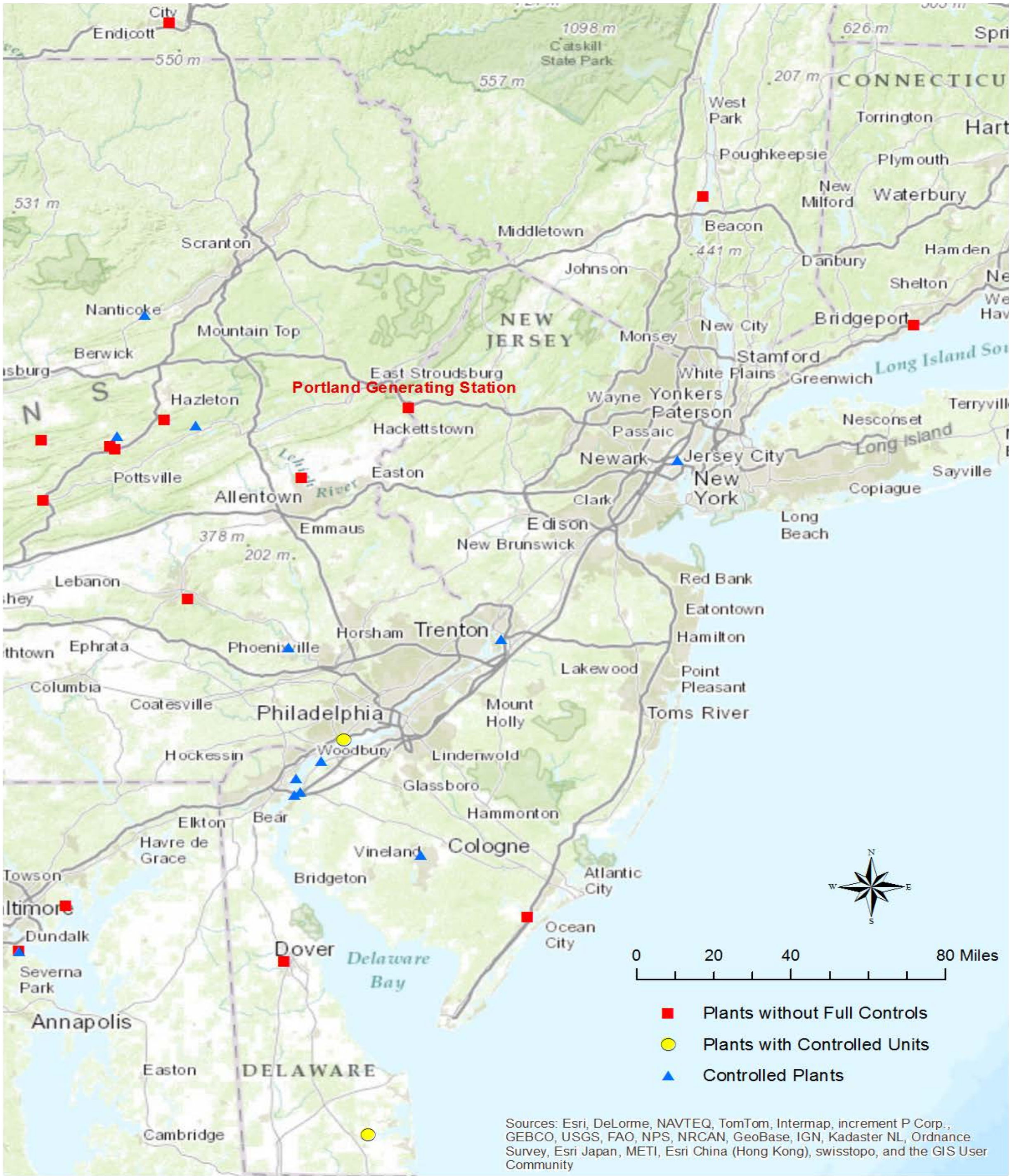

Figure 2: Coal-Fired Power Plants in New Jersey and the Nearby Region

Note: This map is obtained through the ArcGIS Online from the U.S. Environmental Protection Agency, the Office of Enforcement and Compliance Assurance, and the Office of Compliance.

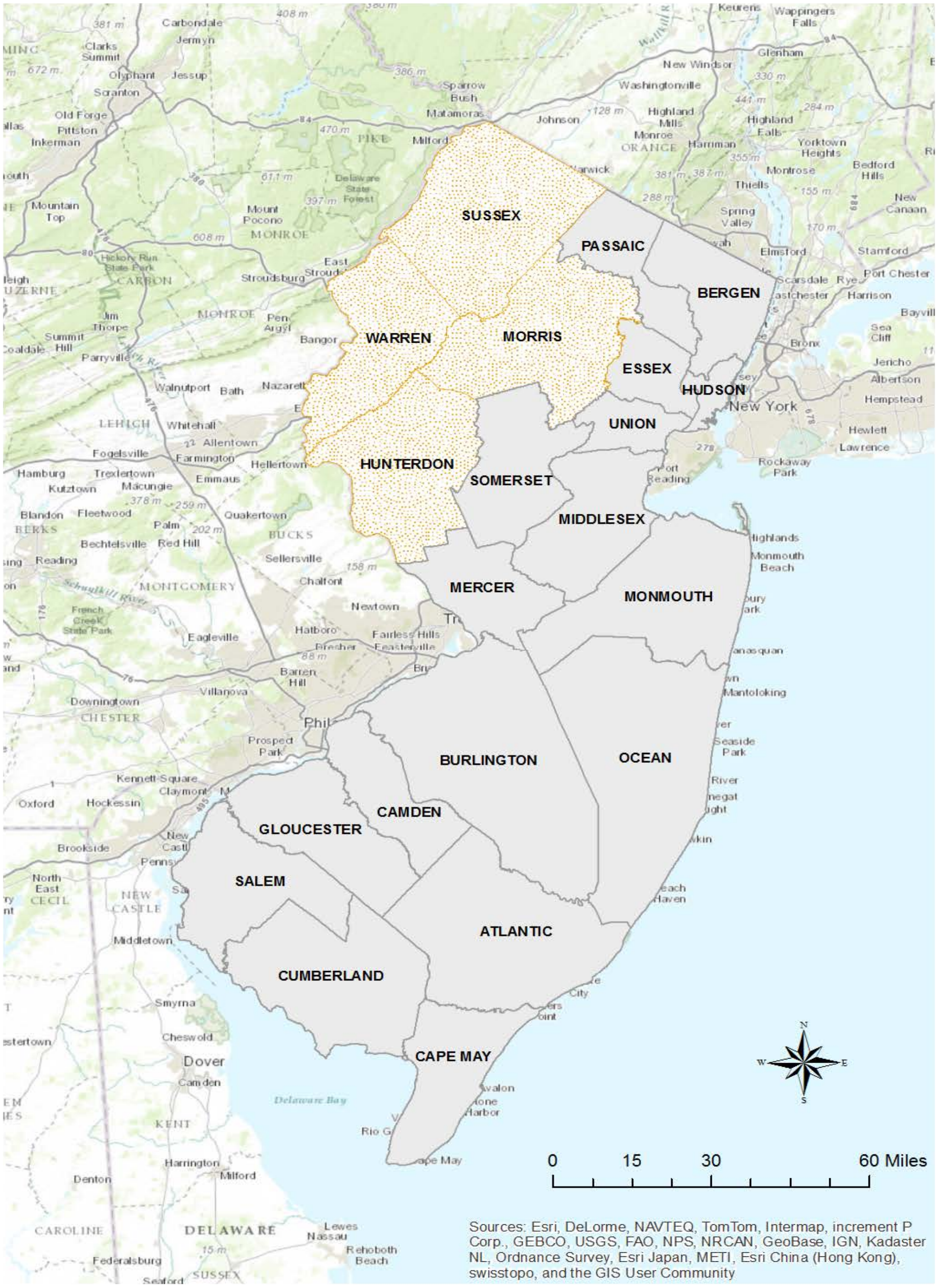

Figure 3: New Jersey Counties

Note: The four highlighted counties (Hunterdon, Morris, Sussex and Warren) are the impacted area identified by the two petitions of the New Jersey Department of Environmental Protection filed with the U.S. Environmental Protection Agency in 2010.

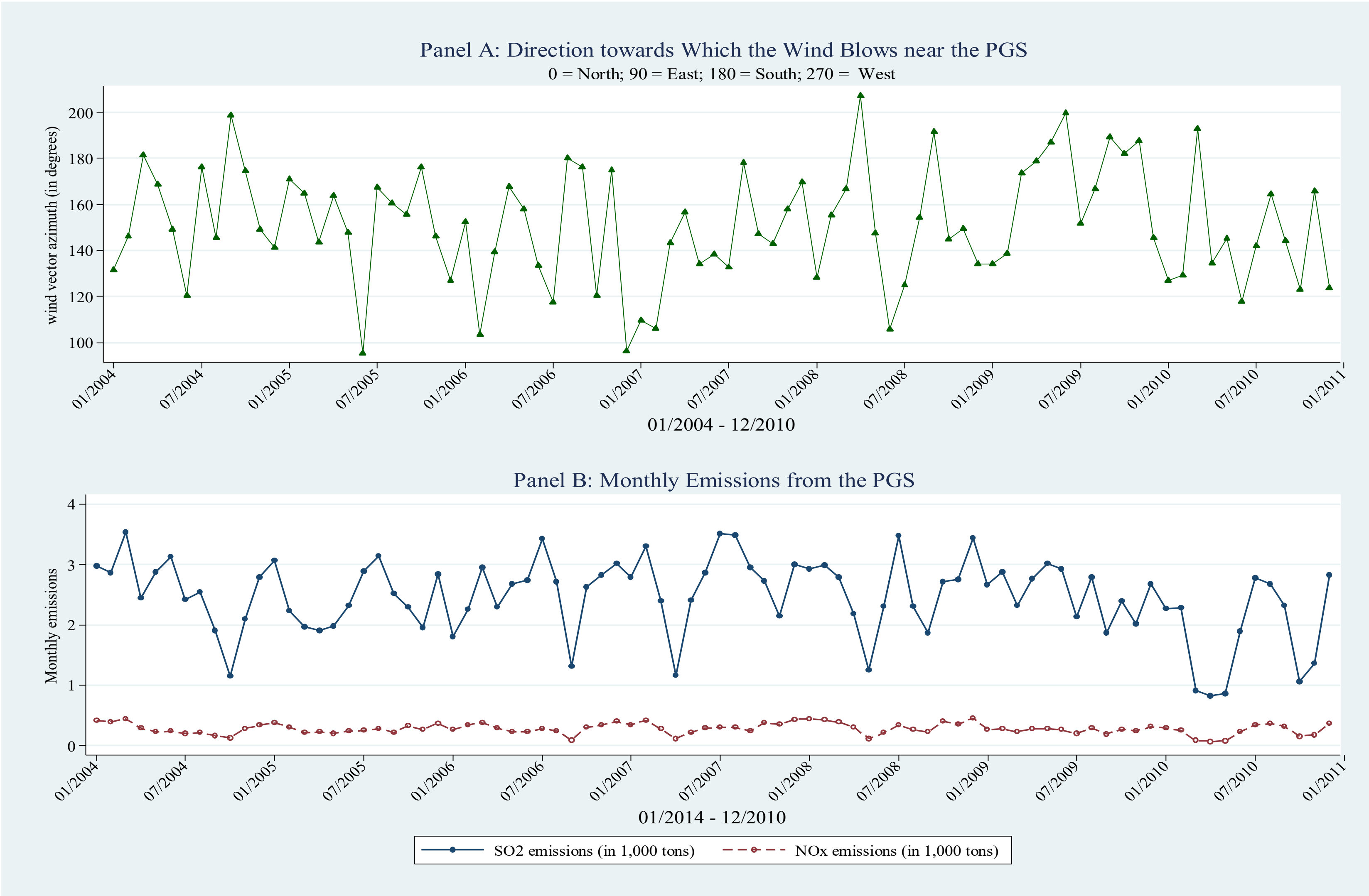

Figure 4: Monthly Sulfur Dioxide and Nitrogen Oxides Emissions from the Portland Generating Station (PGS) and the Monthly Average Wind Directions near the PGS

Note: The power plant's emission data are from the EPA's Air Markets Program Data (AMPD). The wind direction data are purchased from weathersource.com. The sample period is January 2004–December 2010.

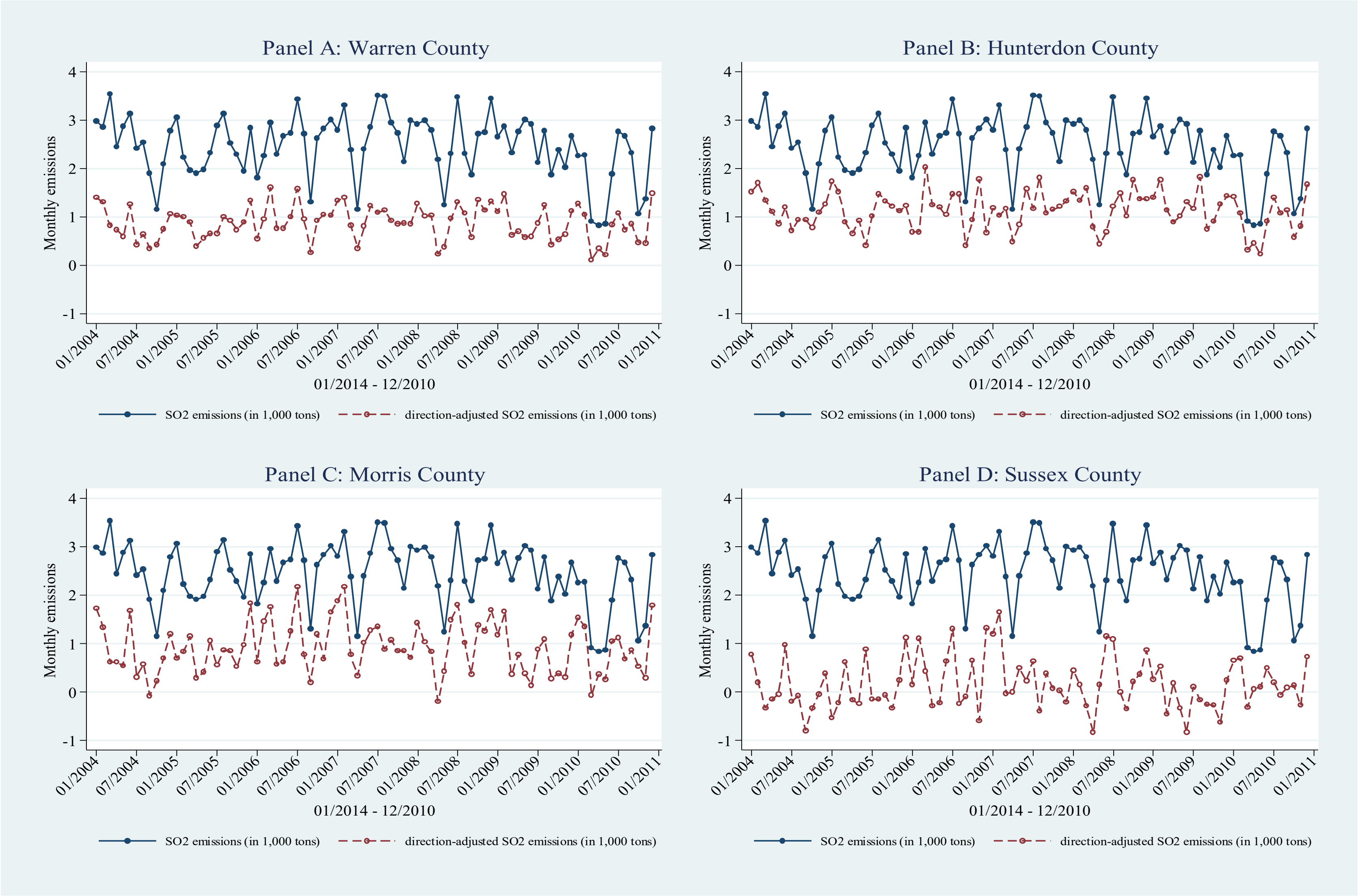

Figure 5: Monthly Sulfur Dioxide Emissions from the Portland Generating Station (PGS) Adjusted by the Wind Direction near the PGS for the Four New Jersey Counties

Note: The power plant's emission data are from the EPA's Air Markets Program Data (AMPD). The wind direction data are purchased from weathersource.com. The sample period is January 2004–December 2010. The four highlighted counties (Hunterdon, Morris, Sussex and Warren) are the impacted area identified by the two petitions of the New Jersey Department of Environmental Protection filed with the U.S. Environmental Protection Agency in 2010.

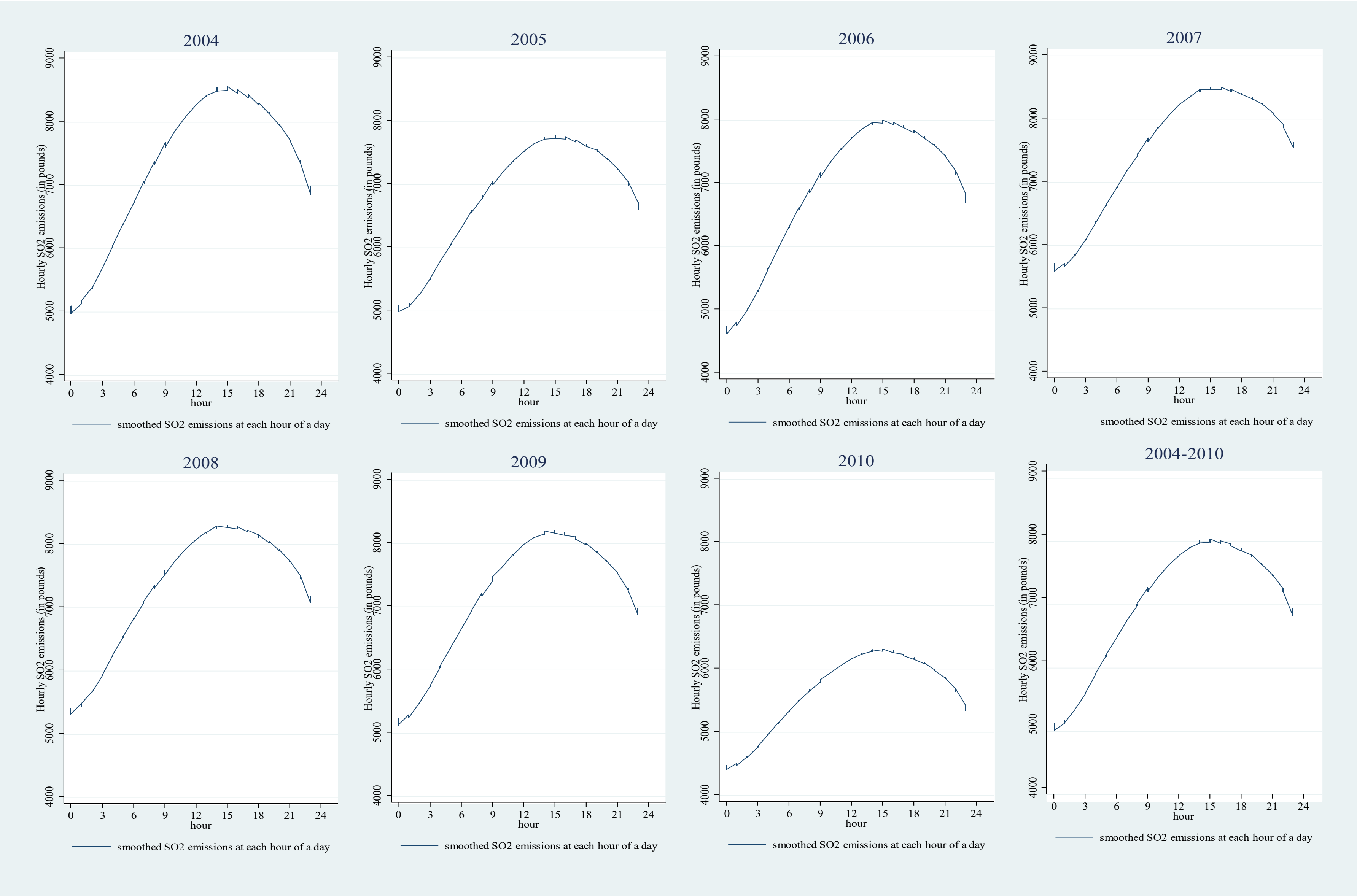

Figure 6: Hourly Sulfur Dioxide Emissions from the Portland Generating Station (PGS)

Note: The power plant's emission data are from the EPA's Air Markets Program Data (AMPD). The hourly emissions are measured in pounds and at each hour of a day (0:00 through 23:00). Depicted in the panels are locally weighted scatterplot smoothing (i.e., "lowess") values with the default bandwidth 0.8 used. The sample period is January 2004–December 2010.

Table 1: Summary Statistics, Part I

Panel A: Portland Generating Station (PGS), a coal-fired power plant in Pennsylvania	
Power plant SO_2 monthly emissions (in 1,000 tons)	2.469
	(0.630)
Power plant SO_2 monthly emissions (in 1,000 tons), direction-adjusted	0.806
	(0.614)
Power plant NO_x monthly emissions (in 1,000 tons)	0.275
	(0.088)
Power plant NO_x monthly emissions (in 1,000 tons), direction-adjusted	0.092
	(0.075)
Monthly average direction (in degrees) towards which the wind near the PGS is blowing	151.458
(i.e., wind direction): 0 = North, 90 = East, 180 = South, 270 = West	(24.863)

Panel B: New Jersey counties included in the estimation sample	Hunterdon	Morris	Sussex	Warren
Distance (in miles) between a New Jersey zip code centroid and the PGS	25.483	31.117	26.017	12.574
	(6.055)	(6.174)	(6.747)	(2.873)
Direction (in degrees) towards which a New Jersey zip code centroid is located from the	157.729	96.342	62.039	137.229
PGS (i.e., azimuth): 0 = North, 90 = East, 180 = South; 270 = West	(12.457)	(9.776)	(13.702)	(46.367)
Being downwind of the PGS, measured by the cosine function of (monthly wind direction	0.470	0.335	0.077	0.350
near the PGS - NJ zip code centroid azimuth)	(0.120)	(0.188)	(0.231)	(0.212)
Number of zip codes in the four-county estimation sample	26	50	23	17
Number of observations in the four-county estimation sample	6,723	29,993	8,714	6,379
Total number of zip codes in the four-county estimation sample		116		
Total number of observations in the four-county estimation sample		51,809		

Note: Means and standard deviations (in parentheses) are reported for each variable listed in this table. The power plant's emission data are from the EPA's Air Markets Program Data (AMPD). The wind direction data are purchased from weathersource.com. The zip code database is purchased from http://www.zip-codes.com/zip-code-statistics.asp. The sample period is January 2004–December 2010. Azimuth is used for the determination of the wind direction near the PGS and also the zip code direction relative to the PGS. The calculation and interpretation of azimuth are given in the text. The direction-adjusted sulfur dioxide (or nitrogen oxides) emissions (in 1,000 tons) from the power plant are measured by first taking the product of (1) the daily sulfur dioxide (or nitrogen oxides) emissions from the power plant and (2) the cosine function of the difference between daily wind direction (where the wind blows) near the power plant and the New Jersey zip code centroid azimuth (relative to the power plant), and then aggregating the aforementioned product to the zip code-monthly level.

Table 2: Summary Statistics, Part II

Panel A: New Jersey counties	Hunterdon		Morris		Sussex		Warren		All Four Counties	
Estimation sample summary statistics	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Birth weight (in grams) of full-term births	3,471.281	435.552	3,438.338	453.102	3,487.501	463.013	3,455.474	468.631	3,452.992	454.889
Full-term low birth weight (1/0): birth weight < 2,500 grams and gestation ≥ 37 weeks	0.013	0.114	0.018	0.133	0.015	0.121	0.020	0.139	0.017	0.129
Female (1/0)	0.486	0.500	0.488	0.500	0.492	0.500	0.496	0.500	0.490	0.500
Mother's age	32.910	5.253	32.280	5.282	31.269	5.458	30.662	5.711	31.993	5.406
Mother is White (1/0)	0.929	0.256	0.818	0.386	0.948	0.221	0.905	0.293	0.865	0.342
Mother is Black (1/0)	0.015	0.120	0.030	0.171	0.019	0.136	0.036	0.187	0.027	0.162
Mother is Hispanic (1/0)	0.093	0.291	0.175	0.380	0.077	0.266	0.102	0.302	0.139	0.346
Mother completed a four-year college or higher (1/0)	0.635	0.481	0.618	0.486	0.463	0.499	0.434	0.496	0.572	0.495
Mother is married (1/0)	0.877	0.328	0.854	0.353	0.828	0.377	0.773	0.419	0.843	0.364
Number of observations in the estimation sample	6,723		29,993		8,714		6,379		51,809	
Panel B: New Jersey counties	Hunterdon		Morris		Sussex		Warren		All New Jersey Counties	
Full sample summary statistics	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Birth weight (in grams)	3,417.529	492.484	3,389.035	503.813	3,435.285	515.797	3,406.624	517.077	3,328.262	518.956
Low birth weight (1/0): birth weight < 2,500 grams	0.036	0.186	0.040	0.197	0.038	0.190	0.041	0.199	0.053	0.225
Gestational length (in weeks)	39.234	1.801	39.354	1.936	39.391	2.021	39.333	1.954	39.244	2.193
Preterm (1/0): gestation < 37 weeks	0.073	0.260	0.073	0.260	0.076	0.265	0.073	0.261	0.097	0.296
Female (1/0)	0.482	0.500	0.486	0.500	0.491	0.500	0.495	0.500	0.488	0.500
Mother's age	32.906	5.306	32.272	5.319	31.294	5.513	30.670	5.766	29.752	6.079
Mother is White (1/0)	0.927	0.261	0.817	0.386	0.948	0.222	0.902	0.298	0.699	0.459
Mother is Black (1/0)	0.016	0.125	0.032	0.175	0.019	0.138	0.040	0.195	0.174	0.379
Mother is Hispanic (1/0)	0.095	0.293	0.179	0.383	0.078	0.267	0.102	0.303	0.266	0.442
Mother completed a four-year college or higher (1/0)	0.628	0.483	0.612	0.487	0.454	0.498	0.427	0.495	0.385	0.487
Mother is married (1/0)	0.873	0.333	0.849	0.358	0.823	0.382	0.769	0.422	0.659	0.474
Number of observations in the full sample	7,252		32,360		9,431		6,886		678,537	

Note: Birth data are from the birth certificates provided by the New Jersey Department of Health. The sample period is January 2004–December 2010. The birth certificate data provided to our study are recorded as repeated cross sections. The summary statistics ae based on the samples including live and singleton births (with multiple births excluded).

Table 3: Impacts of Being Downwind of the Power Plant on Full-Term Low Birth Weight

New Jersey counties included:	Hunterdon, Morris, Sussex and Warren			Hunterdon, Morris and Sussex		
	(1)	(2)	(3)	(4)	(5)	(6)
Being downwind of the power plant:						
During the birth month	-0.0015	-0.0014	-0.0015	-0.0018	-0.0018	-0.0018
	(0.0030)	(0.0029)	(0.0029)	(0.0032)	(0.0032)	(0.0032)
During the 1st month before birth	-0.0014	-0.0011	-0.0011	-0.0023	-0.0022	-0.0023
	(0.0033)	(0.0033)	(0.0034)	(0.0028)	(0.0028)	(0.0028)
During the 2nd month before birth	-0.0045	-0.0046	-0.0046	-0.0038	-0.0039	-0.0039
	(0.0030)	(0.0030)	(0.0030)	(0.0030)	(0.0030)	(0.0030)
During the 3rd month before birth	0.0014	0.0018	0.0018	0.0017	0.0022	0.0022
	(0.0035)	(0.0035)	(0.0035)	(0.0036)	(0.0036)	(0.0037)
During the 4th month before birth	0.0002	0.0001	0.0001	0.0006	0.0005	0.0005
	(0.0033)	(0.0033)	(0.0033)	(0.0034)	(0.0034)	(0.0034)
During the 5th month before birth	0.0044	0.0044	0.0044	0.0023	0.0024	0.0025
	(0.0035)	(0.0035)	(0.0036)	(0.0036)	(0.0036)	(0.0038)
During the 6th month before birth	0.0021	0.0022	0.0022	0.0025	0.0026	0.0026
	(0.0035)	(0.0034)	(0.0035)	(0.0036)	(0.0036)	(0.0037)
During the 7th month before birth	0.0042	0.0044	0.0045	0.0043	0.0046	0.0045
	(0.0034)	(0.0035)	(0.0034)	(0.0033)	(0.0033)	(0.0033)
During the 8th month before birth	0.0093***	0.0092***	0.0093***	0.0090***	0.0089***	0.0088**
	(0.0033)	(0.0032)	(0.0034)	(0.0032)	(0.0031)	(0.0034)
During the month after birth			0.0003			-0.0007
			(0.0043)			(0.0046)
Other control variables:						
Zip code fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Linear and quadratic time trend	Yes	Yes	Yes	Yes	Yes	Yes
Individual-level demographic variables	No	Yes	Yes	No	Yes	Yes
Number of zip codes	116	116	116	99	99	99
Number of observations	51,809	51,809	51,809	45,430	45,430	45,430

Note: Birth data are from the birth certificates provided by the New Jersey Department of Health. The wind direction data are purchased from weathersource.com. The zip code database is purchased from http://www.zip-codes.com/zip-code-statistics.asp. The sample period is January 2004–December 2010. Full-term low birth weight is represented by a binary variable (1/0), which equals one for the babies with birth weight below 2,500 grams and gestational length greater than or equal to 37 weeks, and zero otherwise. Being downwind of the power plant is measured by the cosine function of the difference between monthly wind direction (where the wind blows) near the power plant and the New Jersey zip code centroid azimuth (relative to the power plant). The calculation and interpretation of azimuth are given in the text. Linear and quadratic time trend are represented by the linear and quadratic terms of the consecutive integers generated from all year-month pairs (January 2004–December 2010). Individual level demographic variables controlled for are sex of the baby (1/0), mother's age, dummy variables (1/0) for mother's race and ethnicity (White, Black, Hispanic), mother having completed a four-year college or higher (1/0), and mother being married (1/0). Zip code fixed effects are used for all specifications. Standard errors (reported in parentheses) are clustered at the zip code level. * Significant at the 10% level; ** Significant at the 5% level; *** Significant at the 1% level.

Table 4: Impacts of Being Downwind of the Power Plant on Full-Term Low Birth Weight

New Jersey zip codes included:	Within 40 miles of the power plant			Within 35 miles of the power plant		
	(1)	(2)	(3)	(4)	(5)	(6)
Being downwind of the power plant:						
During the birth month	-0.0004	-0.0004	-0.0006	0.0004	0.0005	0.0003
	(0.0029)	(0.0029)	(0.0029)	(0.0031)	(0.0031)	(0.0032)
During the 1st month before birth	-0.0018	-0.0016	-0.0015	-0.0001	-0.0001	0.0001
	(0.0031)	(0.0031)	(0.0031)	(0.0038)	(0.0039)	(0.0039)
During the 2nd month before birth	-0.0027	-0.0029	-0.0028	-0.0054	-0.0054	-0.0053
	(0.0028)	(0.0028)	(0.0028)	(0.0034)	(0.0034)	(0.0034)
During the 3rd month before birth	0.0019	0.0021	0.0021	0.0023	0.0026	0.0025
	(0.0031)	(0.0031)	(0.0031)	(0.0037)	(0.0037)	(0.0037)
During the 4th month before birth	-0.0000	0.0001	0.0001	0.0011	0.0012	0.0012
	(0.0027)	(0.0027)	(0.0027)	(0.0035)	(0.0035)	(0.0036)
During the 5th month before birth	0.0041	0.0041	0.0039	0.0032	0.0032	0.0029
	(0.0030)	(0.0030)	(0.0031)	(0.0038)	(0.0038)	(0.0039)
During the 6th month before birth	0.0009	0.0008	0.0009	0.0035	0.0034	0.0035
	(0.0032)	(0.0031)	(0.0033)	(0.0030)	(0.0030)	(0.0031)
During the 7th month before birth	0.0022	0.0025	0.0026	0.0005	0.0007	0.0008
	(0.0030)	(0.0030)	(0.0030)	(0.0036)	(0.0037)	(0.0036)
During the 8th month before birth	0.0063**	0.0063**	0.0066**	0.0108***	0.0107***	0.0112***
	(0.0029)	(0.0028)	(0.0030)	(0.0032)	(0.0032)	(0.0031)
During the month after birth			0.0015			0.0023
			(0.0038)			(0.0041)
Other control variables:						
Zip code fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Linear and quadratic time trend	Yes	Yes	Yes	Yes	Yes	Yes
Individual-level demographic variables	No	Yes	Yes	No	Yes	Yes
Number of zip codes	147	147	147	112	112	112
Number of observations	77,708	77,708	77,708	48,997	48,997	48,997

Note: Birth data are from the birth certificates provided by the New Jersey Department of Health. The wind direction data are purchased from weathersource.com. The zip code database is purchased from http://www.zip-codes.com/zip-code-statistics.asp. The sample period is January 2004–December 2010. The New Jersey counties included in the 40-mile and 35-mile samples and the associated summary statistics are reported in Appendix Table 1. Full-term low birth weight is represented by a binary variable (1/0), which equals one for the babies with birth weight below 2,500 grams and gestational length greater than or equal to 37 weeks, and zero otherwise. Being downwind of the power plant is measured by the cosine function of the difference between monthly wind direction (where the wind blows) near the power plant and the New Jersey zip code centroid azimuth (relative to the power plant). The calculation and interpretation of azimuth are given in the text. Linear and quadratic time trend are represented by the linear and quadratic terms of the consecutive integers generated from all year-month pairs (January 2004–December 2010). Individual level demographic variables controlled for are sex of the baby (1/0), mother's age, dummy variables (1/0) for mother's race and ethnicity (White, Black, Hispanic), mother having completed a four-year college or higher (1/0), and mother being married (1/0). Zip code fixed effects are used for all specifications. Standard errors (reported in parentheses) are clustered at the zip code level. * Significant at the 10% level; ** Significant at the 5% level; *** Significant at the 1% level.

Table 5: Impacts of Being Downwind of the Power Plant on Full-Term Low Birth Weight

New Jersey regions included:	Cape May, Hudson and Salem Counties	Zip codes that are at least 80 miles away from the power plant
	(1)	(2)
Being downwind of the power plant:		
During the birth month	-0.0011	0.0028
	(0.0036)	(0.0056)
During the 1st month before birth	0.0021	0.0024
	(0.0046)	(0.0050)
During the 2nd month before birth	0.0040	-0.0074
	(0.0055)	(0.0052)
During the 3rd month before birth	0.0041	-0.0054
	(0.0046)	(0.0062)
During the 4th month before birth	-0.0013	-0.0049
	(0.0040)	(0.0049)
During the 5th month before birth	-0.0038	-0.0082
	(0.0044)	(0.0054)
During the 6th month before birth	-0.0040	-0.0079
	(0.0037)	(0.0049)
During the 7th month before birth	-0.0004	-0.0024
	(0.0059)	(0.0042)
During the 8th month before birth	0.0027	-0.0041
	(0.0039)	(0.0050)
Other control variables:		
Zip code fixed effects	Yes	Yes
Linear and quadratic time trend	Yes	Yes
Individual-level demographic variables	Yes	Yes
Number of zip codes	51	121
Number of observations	56,054	67,573

Note: Birth data are from the birth certificates provided by the New Jersey Department of Health. The wind direction data are purchased from weathersource.com. The zip code database is purchased from http://www.zip-codes.com/zip-code-statistics.asp. The sample period is January 2004–December 2010. Summary statistics for the two samples (used for columns 1 and 2) are reported in Appendix Table 1. Full-term low birth weight is represented by a binary variable (1/0), which equals one for the babies with birth weight below 2,500 grams and gestational length greater than or equal to 37 weeks, and zero otherwise. Being downwind of the power plant is measured by the cosine function of the difference between monthly wind direction (where the wind blows) near the power plant and the New Jersey zip code centroid azimuth (relative to the power plant). The calculation and interpretation of azimuth are given in the text. Linear and quadratic time trend are represented by the linear and quadratic terms of the consecutive integers generated from all year-month pairs (January 2004–December 2010). Individual level demographic variables controlled for are sex of the baby (1/0), mother's age, dummy variables (1/0) for mother's race and ethnicity (White, Black, Hispanic), mother having completed a four-year college or higher (1/0), and mother being married (1/0). Zip code fixed effects are used for all specifications. Standard errors (reported in parentheses) are clustered at the zip code level. * Significant at the 10% level; ** Significant at the 5% level; *** Significant at the 1% level.

Table 6: Falsification Checks on the Pseudo Impacts of Being Downwind of the Power Plant on Full-Term Low Birth Weight

New Jersey zip codes included:	Within 40 miles of the power plant (1)	Within 35 miles of the power plant (2)
Being downwind of the power plant:		
During the 6th month after birth	-0.0025	-0.0033
	(0.0029)	(0.0034)
During the 7th month after birth	0.0031	0.0041
	(0.0029)	(0.0032)
During the 8th month after birth	0.0009	0.0015
	(0.0024)	(0.0027)
During the 9th month after birth	-0.0023	-0.0045
	(0.0031)	(0.0032)
During the 10th month after birth	0.0031	0.0021
	(0.0030)	(0.0034)
During the 11th month after birth	-0.0006	-0.0003
	(0.0029)	(0.0037)
During the 12th month after birth	0.0040	0.0047
	(0.0027)	(0.0038)
Other control variables:		
Zip code fixed effects	Yes	Yes
Linear and quadratic time trend	Yes	Yes
Individual-level demographic variables	Yes	Yes
Number of zip codes	147	112
Number of observations	77,708	48,997

Note: Birth data are from the birth certificates provided by the New Jersey Department of Health. The wind direction data are purchased from weathersource.com. The zip code database is purchased from http://www.zip-codes.com/zip-code-statistics.asp. The sample period is January 2004–December 2010. Summary statistics for the two samples (used for columns 1 and 2) are reported in Appendix Table 1. Full-term low birth weight is represented by a binary variable (1/0), which equals one for the babies with birth weight below 2,500 grams and gestational length greater than or equal to 37 weeks, and zero otherwise. Being downwind of the power plant is measured by the cosine function of the difference between monthly wind direction (where the wind blows) near the power plant and the New Jersey zip code centroid azimuth (relative to the power plant). The calculation and interpretation of azimuth are given in the text. Linear and quadratic time trend are represented by the linear and quadratic terms of the consecutive integers generated from all year-month pairs (January 2004–December 2010). Individual level demographic variables controlled for are sex of the baby (1/0), mother's age, dummy variables (1/0) for mother's race and ethnicity (White, Black, Hispanic), mother having completed a four-year college or higher (1/0), and mother being married (1/0). Zip code fixed effects are used for all specifications. Standard errors (reported in parentheses) are clustered at the zip code level. * Significant at the 10% level; ** Significant at the 5% level; *** Significant at the 1% level.

Table 7: Impacts of Power Plant Sulfur Dioxide Emissions on Full-Term Low Birth Weight

New Jersey regions included:	Hunterdon, Morris and Sussex Counties		Hunterdon and Morris Counties		Zip codes within 40 miles of the power plant		Cape May, Hudson and Salem Counties
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Being exposed to sulfur dioxide emissions (in 1,000 tons) from the power plant, direction-adjusted:							
During the birth month	-0.0002	-0.0002	-0.0004	-0.0005	0.0001	0.0000	-0.0005
	(0.0012)	(0.0012)	(0.0013)	(0.0013)	(0.0009)	(0.0009)	(0.0011)
During the 1st month before birth	-0.0011	-0.0010	-0.0016	-0.0016	-0.0010	-0.0009	0.0014
	(0.0011)	(0.0011)	(0.0013)	(0.0013)	(0.0011)	(0.0011)	(0.0015)
During the 2nd month before birth	-0.0019	-0.0019	-0.0013	-0.0013	-0.0008	-0.0009	0.0022
	(0.0012)	(0.0012)	(0.0014)	(0.0014)	(0.0011)	(0.0011)	(0.0023)
During the 3rd month before birth	0.0012	0.0014	0.0002	0.0004	0.0010	0.0011	0.0005
	(0.0013)	(0.0013)	(0.0014)	(0.0014)	(0.0011)	(0.0011)	(0.0016)
During the 4th month before birth	-0.0006	-0.0007	-0.0001	-0.0002	-0.0001	-0.0001	0.0003
	(0.0010)	(0.0010)	(0.0012)	(0.0012)	(0.0009)	(0.0009)	(0.0014)
During the 5th month before birth	0.0012	0.0013	0.0016	0.0017	0.0010	0.0010	-0.0014
	(0.0013)	(0.0013)	(0.0015)	(0.0015)	(0.0010)	(0.0010)	(0.0015)
During the 6th month before birth	0.0012	0.0012	0.0010	0.0010	0.0003	0.0002	-0.0012
	(0.0012)	(0.0012)	(0.0015)	(0.0014)	(0.0011)	(0.0011)	(0.0012)
During the 7th month before birth	0.0017	0.0018	0.0010	0.0010	0.0005	0.0006	0.0003
	(0.0014)	(0.0014)	(0.0017)	(0.0017)	(0.0012)	(0.0013)	(0.0019)
During the 8th month before birth	0.0024**	0.0024**	0.0025*	0.0025*	0.0017*	0.0017*	-0.0003
	(0.0012)	(0.0012)	(0.0014)	(0.0014)	(0.0010)	(0.0009)	(0.0012)
Other control variables:							
Zip code fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Linear and quadratic time trend	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Individual-level demographic variables	No	Yes	No	Yes	No	Yes	Yes
Number of zip codes	99	99	76	76	147	147	51
Number of observations	45,430	45,430	36,716	36,716	77,708	77,708	56,054

Note: Birth data are from the birth certificates provided by the New Jersey Department of Health. The power plant's emission data are from the EPA's Air Markets Program Data (AMPD). The wind direction data are purchased from weathersource.com. The zip code database is purchased from http://www.zip-codes.com/zip-code-statistics.asp. The sample period is January 2004–December 2010. Full-term low birth weight is represented by a binary variable (1/0), which equals one for the babies with birth weight below 2,500 grams and gestational length greater than or equal to 37 weeks, and zero otherwise. Being exposed to sulfur dioxide emissions (in 1,000 tons) from the power plant (direction adjusted) is measured by first taking the product of (1) the daily sulfur dioxide emissions from the power plant and (2) the cosine function of the difference between daily wind direction (where the wind blows) near the power plant and the New Jersey zip code centroid azimuth (relative to the power plant), and then aggregating the aforementioned product to the zip code-monthly level. The calculation and interpretation of azimuth are given in the text. Linear and quadratic time trend are represented by the linear and quadratic terms of the consecutive integers generated from all year-month pairs (January 2004–December 2010). Individual level demographic variables controlled for are sex of the baby (1/0), mother's age, dummy variables (1/0) for mother's race and ethnicity (White, Black, Hispanic), mother having completed a four-year college or higher (1/0), and mother being married (1/0). Zip code fixed effects are used for all specifications. Standard errors (reported in parentheses) are clustered at the zip code level. * Significant at the 10% level; ** Significant at the 5% level; *** Significant at the 1% level.

Table 8: Impacts of Power Plant Nitrogen Oxides Emissions on Full-Term Low Birth Weight

New Jersey regions included:	Hunterdon, Morris and Sussex Counties		Hunterdon and Morris Counties		Zip codes within 40 miles of the power plant		Cape May, Hudson and Salem Counties
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Being exposed to nitrogen oxides emissions (in 1,000 tons) from the power plant, direction-adjusted:							
During the birth month	0.0002	0.0000	-0.0001	-0.0005	0.0032	0.0027	-0.0082
	(0.0098)	(0.0097)	(0.0111)	(0.0109)	(0.0072)	(0.0072)	(0.0084)
During the 1st month before birth	-0.0009	-0.0006	-0.0086	-0.0083	-0.0030	-0.0026	0.0091
	(0.0086)	(0.0085)	(0.0100)	(0.0099)	(0.0089)	(0.0089)	(0.0128)
During the 2nd month before birth	-0.0149	-0.0152	-0.0086	-0.0088	-0.0070	-0.0080	0.0096
	(0.0094)	(0.0095)	(0.0112)	(0.0113)	(0.0084)	(0.0084)	(0.0179)
During the 3rd month before birth	0.0123	0.0138	0.0024	0.0040	0.0124	0.0135	0.0035
	(0.0094)	(0.0095)	(0.0096)	(0.0097)	(0.0084)	(0.0084)	(0.0135)
During the 4th month before birth	-0.0086	-0.0090	-0.0057	-0.0060	-0.0024	-0.0023	0.0019
	(0.0084)	(0.0083)	(0.0101)	(0.0100)	(0.0070)	(0.0070)	(0.0114)
During the 5th month before birth	0.0065	0.0071	0.0099	0.0110	0.0053	0.0053	-0.0177
	(0.0096)	(0.0097)	(0.0109)	(0.0110)	(0.0077)	(0.0077)	(0.0114)
During the 6th month before birth	0.0063	0.0068	0.0032	0.0038	0.0035	0.0034	-0.0067
	(0.0096)	(0.0096)	(0.0112)	(0.0112)	(0.0079)	(0.0079)	(0.0084)
During the 7th month before birth	0.0061	0.0068	-0.0031	-0.0029	-0.0018	-0.0012	0.0059
	(0.0124)	(0.0126)	(0.0145)	(0.0147)	(0.0105)	(0.0106)	(0.0167)
During the 8th month before birth	0.0165	0.0163	0.0197	0.0198	0.0115	0.0112	0.0050
	(0.0102)	(0.0102)	(0.0122)	(0.0121)	(0.0081)	(0.0080)	(0.0100)
Other control variables:							
Zip code fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Linear and quadratic time trend	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Individual-level demographic variables	No	Yes	No	Yes	No	Yes	Yes
Number of zip codes	99	99	76	76	147	147	51
Number of observations	45,430	45,430	36,716	36,716	77,708	77,708	56,054

Note: Birth data are from the birth certificates provided by the New Jersey Department of Health. The power plant's emission data are from the EPA's Air Markets Program Data (AMPD). The wind direction data are purchased from weathersource.com. The zip code database is purchased from http://www.zip-codes.com/zip-code-statistics.asp. The sample period is January 2004–December 2010. Full-term low birth weight is represented by a binary variable (1/0), which equals one for the babies with birth weight below 2,500 grams and gestational length greater than or equal to 37 weeks, and zero otherwise. Being exposed to nitrogen oxides emissions (in 1,000 tons) from the power plant (direction adjusted) is measured by first taking the product of (1) the daily nitrogen oxides emissions from the power plant and (2) the cosine function of the difference between daily wind direction (where the wind blows) near the power plant and the New Jersey zip code centroid azimuth (relative to the power plant), and then aggregating the aforementioned product to the zip code-monthly level. The calculation and interpretation of azimuth are given in the text. Linear and quadratic time trend are represented by the linear and quadratic terms of the consecutive integers generated from all year-month pairs (January 2004–December 2010). Individual level demographic variables controlled for are sex of the baby (1/0), mother's age, dummy variables (1/0) for mother's race and ethnicity (White, Black, Hispanic), mother having completed a four-year college or higher (1/0), and mother being married (1/0). Zip code fixed effects are used for all specifications. Standard errors (reported in parentheses) are clustered at the zip code level. * Significant at the 10% level; ** Significant at the 5% level; *** Significant at the 1% level.

Table 9: Impacts of Power Plant Emissions on Local Pollution Measured at New Jersey Zip Code Level

New Jersey regions included:	Warren County	Hunterdon and Morris Counties	Hunterdon, Morris and Sussex Counties	Zip codes that are within 40 miles of the power plant	Zip codes that are at least 80 miles away from the power plant
	(1)	(2)	(3)	(4)	(5)
Panel A: Dependent variable—SO_2 (ppb), zip code level, inverse-distance weighted, monthly average of the one-hour daily maximum levels					
Power plant SO_2 monthly emissions (in 1,000 tons), direction-adjusted	2.249***	1.664***	1.752***	1.587***	-0.033
	(0.141)	(0.110)	(0.101)	(0.111)	(0.103)
Number of observations	6,783	37,390	42,056	75,870	59,342
Panel B: Dependent variable—$PM_{2.5}$ ($\mu g/m^3$), zip code level, inverse-distance weighted, monthly average of the one-hour daily maximum levels					
Power plant SO_2 monthly emissions (in 1,000 tons), direction-adjusted	1.034*	1.783***	1.780***	1.800***	0.179
	(0.539)	(0.079)	(0.071)	(0.075)	(0.167)
Number of observations	6,788	39,891	44,816	80,289	47,060
Panel C: Dependent variable—NO_2 (ppb), zip code level, inverse-distance weighted, monthly average of the one-hour daily maximum levels					
Power plant NO_x monthly emissions (in 1,000 tons), direction-adjusted	7.151**	1.169	0.335	-2.100	N/A
	(3.007)	(1.771)	(1.667)	(1.602)	N/A
Number of observations	6,517	39,920	44,530	78,342	N/A
Control variables used in Panels A, B and C:					
Weather variables	Yes	Yes	Yes	Yes	Yes
Linear and quadratic time trend	Yes	Yes	Yes	Yes	Yes
Zip code fixed effects	Yes	Yes	Yes	Yes	Yes

Note: Birth data are from the birth certificates provided by the New Jersey Department of Health. The power plant's emission data are from the EPA's Air Markets Program Data (AMPD). The wind direction data are purchased from weathersource.com. The zip code database is purchased from http://www.zip-codes.com/zip-code-statistics.asp. The pollution data are from the EPA's Air Quality System (AQS). The weather data are from the National Climatic Data Center (NCDC). The sample period is January 2004–December 2010. Full-term low birth weight is represented by a binary variable (1/0), which equals one for the babies with birth weight below 2,500 grams and gestational length greater than or equal to 37 weeks, and zero otherwise. The SO2 (or PM2.5, or NO2) concentrations are computed using the procedures explained in the text, with a 20-mile radius used. The direction-adjusted sulfur dioxide (or nitrogen oxides) emissions (in 1,000 tons) from the power plant are measured by first taking the product of (1) the daily sulfur dioxide (or nitrogen oxides) emissions from the power plant and (2) the cosine function of the difference between daily wind direction (where the wind blows) near the power plant and the New Jersey zip code centroid azimuth (relative to the power plant), and then aggregating the aforementioned product to the zip code-monthly level. The calculation and interpretation of azimuth are given in the text. Weather variables controlled for are monthly high temperature, monthly low temperature, monthly mean temperature, monthly rainfall and monthly snowfall, which are all measured at the zip code level using the procedures explained in the text, with a 20-mile radius used. Summary statistics of the pollution and weather variables are reported in Appendix Table 2. Linear and quadratic time trend are represented by the linear and quadratic terms of the consecutive integers generated from all year-month pairs (January 2004–December 2010). Zip code fixed effects are used for all specifications. Standard errors (reported in parentheses) are clustered at the zip code level. * Significant at the 10% level; ** Significant at the 5% level; *** Significant at the 1% level.

Table 10: Impacts of Being Downwind of the Power Plant on Full-Term Low Birth Weight by Sex of the Baby

New Jersey counties included:	Hunterdon, Morris, Sussex and Warren		Hunterdon, Morris and Sussex		Hunterdon and Morris	
	Male	Female	Male	Female	Male	Female
	(1)	(2)	(3)	(4)	(5)	(6)
Being downwind of the power plant:						
During the birth month	-0.0013	-0.0009	-0.0014	-0.0016	0.0017	-0.0074
	(0.0036)	(0.0049)	(0.0039)	(0.0052)	(0.0044)	(0.0061)
During the 1st month before birth	-0.0015	-0.0006	-0.0035	-0.0007	-0.0032	-0.0051
	(0.0051)	(0.0049)	(0.0041)	(0.0053)	(0.0048)	(0.0064)
During the 2nd month before birth	-0.0106**	0.0019	-0.0091*	0.0020	-0.0079	0.0053
	(0.0047)	(0.0048)	(0.0050)	(0.0048)	(0.0063)	(0.0059)
During the 3rd month before birth	0.0040	-0.0002	0.0061	-0.0016	0.0061	-0.0052
	(0.0047)	(0.0051)	(0.0049)	(0.0052)	(0.0059)	(0.0061)
During the 4th month before birth	-0.0035	0.0038	-0.0039	0.0050	-0.0034	0.0061
	(0.0036)	(0.0055)	(0.0031)	(0.0060)	(0.0037)	(0.0076)
During the 5th month before birth	0.0031	0.0057	0.0011	0.0036	0.0007	0.0077
	(0.0048)	(0.0063)	(0.0048)	(0.0065)	(0.0057)	(0.0068)
During the 6th month before birth	0.0037	0.0005	0.0054	-0.0005	0.0062	-0.0027
	(0.0038)	(0.0065)	(0.0041)	(0.0067)	(0.0050)	(0.0084)
During the 7th month before birth	0.0055	0.0036	0.0062	0.0029	0.0041	0.0027
	(0.0043)	(0.0049)	(0.0044)	(0.0050)	(0.0053)	(0.0064)
During the 8th month before birth	0.0124***	0.0062	0.0125***	0.0055	0.0132***	0.0050
	(0.0043)	(0.0044)	(0.0038)	(0.0047)	(0.0044)	(0.0054)
Other control variables:						
Zip code fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Linear and quadratic time trend	Yes	Yes	Yes	Yes	Yes	Yes
Individual-level demographic variables	Yes	Yes	Yes	Yes	Yes	Yes
Number of observations	26,431	25,368	23,219	22,203	18,794	17,918

Note: Birth data are from the birth certificates provided by the New Jersey Department of Health. The wind direction data are purchased from weathersource.com. The zip code database is purchased from http://www.zip-codes.com/zip-code-statistics.asp. The sample period is January 2004–December 2010. Full-term low birth weight is represented by a binary variable (1/0), which equals one for the babies with birth weight below 2,500 grams and gestational length greater than or equal to 37 weeks, and zero otherwise. Being downwind of the power plant is measured by the cosine function of the difference between monthly wind direction (where the wind blows) near the power plant and the New Jersey zip code centroid azimuth (relative to the power plant). The calculation and interpretation of azimuth are given in the text. Linear and quadratic time trend are represented by the linear and quadratic terms of the consecutive integers generated from all year-month pairs (January 2004–December 2010). Individual level demographic variables controlled for are sex of the baby (1/0), mother's age, dummy variables (1/0) for mother's race and ethnicity (White, Black, Hispanic), mother having completed a four-year college or higher (1/0), and mother being married (1/0). Zip code fixed effects are used for all specifications. Standard errors (reported in parentheses) are clustered at the zip code level. * Significant at the 10% level; ** Significant at the 5% level; *** Significant at the 1% level.

Appendix Table 1: Summary Statistics for the Additional Estimation Samples

Panel A: Within 40 miles of the PGS	Hunterdon	Mercer	Middlesex	Morris	Passaic	Somerset	Sussex	Union	Warren	Combined
Distance (in miles) between a New Jersey zipcode centroid and the PGS	25.483	37.836	38.049	30.553	36.153	33.476	26.017	39.401	12.574	30.060
	(6.055)	(0.000)	(0.224)	(5.889)	(3.871)	(2.995)	(6.747)	(0.577)	(2.873)	(8.225)
Direction (in degrees) towards which a New Jersey zip code centroid is located from the PGS (i.e., azimuth): 0 = North, 90 = East, 180 = South; 270 = West	157.729	155.967	125.691	96.977	73.289	132.540	62.039	117.260	137.229	110.556
	(12.457)	(0.000)	(1.410)	(9.679)	(2.309)	(8.310)	(13.702)	(4.590)	(46.367)	(31.451)
Number of zip codes in the estimation sample	26	1	2	46	4	22	23	6	17	147
Number of observations in the estimation sample	6,723	236	1,777	28,317	2,372	14,090	8,714	9,100	6,379	77,708

Panel B: Within 35 miles of the PGS	Hunterdon	Morris	Passaic	Somerset	Sussex	Warren	Combined
Distance (in miles) between a New Jersey zipcode centroid and the PGS	24.640	27.831	31.299	31.262	24.851	12.574	25.561
	(5.192)	(5.010)	(1.467)	(1.945)	(5.956)	(2.873)	(7.141)
Direction (in degrees) towards which a New Jersey zip code centroid is located from the PGS (i.e., azimuth): 0 = North, 90 = East, 180 = South; 270 = West	157.228	96.620	72.703	129.861	62.468	137.229	109.098
	(12.677)	(9.961)	(0.771)	(7.037)	(14.308)	(46.367)	(35.906)
Number of zip codes in the estimation sample	25	35	2	13	20	17	112
Number of observations in the estimation sample	6,325	19,697	878	7,817	7,901	6,379	48,997

Panel C: At least 80 miles away from the PGS	Atlantic	Burlington	Camden	Cape May	Cumberland	Gloucester	Ocean	Salem	Combined
Distance (in miles) between a New Jersey zipcode centroid and the PGS	105.990	89.230	81.527	126.314	103.060	85.412	85.758	90.846	98.360
	(6.479)	(5.497)	(0.504)	(7.171)	(4.273)	(3.341)	(5.841)	(4.617)	(13.498)
Direction (in degrees) towards which a New Jersey zip code centroid is located from the PGS (i.e., azimuth): 0 = North, 90 = East, 180 = South; 270 = West	165.171	159.131	175.596	173.475	180.461	181.022	147.767	190.110	169.053
	(3.192)	(0.681)	(1.264)	(2.708)	(3.928)	(4.684)	(5.026)	(4.045)	(13.441)
Number of zip codes in the estimation sample	30	2	4	21	21	11	20	12	121
Number of observations in the estimation sample	20,090	64	3,802	5,258	13,431	7,762	13,629	3,537	67,573

Panel D: Three counties far away from the PGS	Cape May	Hudson	Salem	Combined
Distance (in miles) between a New Jersey zipcode centroid and the PGS	126.314	54.936	90.846	63.898
	(7.171)	(1.536)	(4.617)	(22.071)
Direction (in degrees) towards which a New Jersey zip code centroid is located from the PGS (i.e., azimuth): 0 = North, 90 = East, 180 = South; 270 = West	173.475	101.908	190.110	114.186
	(2.708)	(2.884)	(4.045)	(28.798)
Number of zip codes in the estimation sample	21	18	12	51
Number of observations in the estimation sample	5,258	47,259	3,537	56,054

Note: Means and standard deviations (in parentheses) are reported for each variable listed in this table. Birth data are from the birth certificates provided by the New Jersey Department of Health. The zip code database is purchased from http://www.zip-codes.com/zip-code-statistics.asp. The sample period is January 2004–December 2010. Azimuth is used for the zip code direction relative to the PGS. The calculation and interpretation of azimuth are given in the text.

Appendix Table 2: Summary Statistics for the Pollution and Weather Variables

New Jersey counties	Warren	Hunterdon, Morris and Sussex	All New Jersey counties
Panel A: SO_2 (ppb), zip code level, inverse-distance weighted, monthly average of the one-hour daily maximum levels			
SO_2 (ppb)	12.106	8.221	9.221
	(7.448)	(4.191)	(4.778)
Distance (in miles) between a New Jersey zip code centroid and a monitor	13.964	13.509	12.386
	(3.283)	(2.725)	(2.466)
Number of monthly monitor readings within the 20-mile radius	1.895	2.407	5.429
	(0.931)	(1.964)	(3.010)
Number of observations	6,783	42,056	595,524
Panel B: $PM_{2.5}$ (μg/m^3), zip code level, inverse-distance weighted, monthly average of the one-hour daily maximum levels			
$PM_{2.5}$ (μg/m^3)	10.871	10.532	11.727
	(3.776)	(3.660)	(3.548)
Distance (in miles) between a New Jersey zip code centroid and a monitor	13.967	13.434	12.378
	(3.283)	(2.707)	(2.386)
Number of monthly monitor readings within the 20-mile radius	2.203	4.327	10.096
	(0.630)	(3.152)	(7.115)
Number of observations	6,788	44,816	640,995
Panel C: NO_2 (ppb), zip code level, inverse-distance weighted, monthly average of the one-hour daily maximum levels			
NO_2 (ppb)	18.475	23.194	33.399
	(7.348)	(10.142)	(8.939)
Distance (in miles) between a New Jersey zip code centroid and a monitor	14.007	13.399	12.527
	(3.340)	(2.688)	(2.195)
Number of monthly monitor readings within the 20-mile radius	1.428	2.053	4.757
	(0.495)	(1.342)	(2.340)
Number of observations	6,517	44,530	550,568
Panel D: Weather variables, zip code level, inverse-distance weighted, monthly averages from weather stations			
Low temperature (in Fahrenheit)	41.884	42.770	44.848
	(15.131)	(15.195)	(15.315)
High temperature (in Fahrenheit)	63.369	63.257	64.490
	(16.857)	(16.883)	(16.696)
Mean temperature (in Fahrenheit)	52.610	53.012	54.672
	(15.923)	(15.987)	(15.945)
Rainfall (in inches)	4.414	4.080	3.972
	(2.990)	(2.290)	(2.211)
Snowfall (in inches)	2.050	2.030	1.755
	(4.655)	(4.380)	(4.285)
Number of observations	6,948	49,396	680,515

Note: Means and standard deviations (in parentheses) are reported for each variable listed in this table. Birth data are from the birth certificates provided by the New Jersey Department of Health. The zip code database is purchased from http://www.zip-codes.com/zip-code-statistics.asp. The pollution data are from the EPA's Air Quality System (AQS). The weather data are from the National Climatic Data Center (NCDC). The sample period is January 2004–December 2010. The SO2 (or PM2.5, or NO2) concentrations are computed using the procedures explained in the text, with a 20-mile radius used. Weather variables are all measured at the zip code level using the procedures explained in the text, with a 20-mile radius used.

Appendix Table 3: Impacts of Power Plant Emissions on Local Pollution Measured at New Jersey Zip Code Level (15-mile radius used)

New Jersey regions included:	Warren County	Hunterdon and Morris Counties	Hunterdon, Morris and Sussex Counties	Zip codes that are within 40 miles of the power plant	Zip codes that are at least 80 miles away from the power plant
	(1)	(2)	(3)	(4)	(5)
Panel A: SO_2 (ppb), zip code level, inverse-distance weighted, monthly average of the one-hour daily maximum levels, used as the dependent variable					
Power plant SO_2 monthly emissions (in 1,000 tons), direction-adjusted	2.963***	1.977***	1.991***	1.774***	0.014
	(0.419)	(0.132)	(0.121)	(0.186)	(0.115)
Number of observations	5,772	28,384	30,364	56,428	48,637
Panel B: $PM_{2.5}$ ($\mu g/m^3$), zip code level, inverse-distance weighted, monthly average of the one-hour daily maximum levels, used as the dependent variable					
Power plant SO_2 monthly emissions (in 1,000 tons), direction-adjusted	0.848	1.883***	1.901***	1.882***	0.284
	(0.765)	(0.088)	(0.084)	(0.083)	(0.238)
Number of observations	6,018	38,699	40,679	73,070	33,768
Panel C: NO_2 (ppb), zip code level, inverse-distance weighted, monthly average of the one-hour daily maximum levels, used as the dependent variable					
Power plant NO_x monthly emissions (in 1,000 tons), direction-adjusted	9.850***	3.062	2.897	0.132	N/A
	(0.645)	(1.921)	(1.809)	(1.854)	N/A
Number of observations	4,502	31,917	33,897	64,974	N/A
Control variables used in Panels A, B and C:					
Weather variables	Yes	Yes	Yes	Yes	Yes
Linear and quadratic time trend	Yes	Yes	Yes	Yes	Yes
Zip code fixed effects	Yes	Yes	Yes	Yes	Yes

Note: Birth data are from the birth certificates provided by the New Jersey Department of Health. The power plant's emission data are from the EPA's Air Markets Program Data (AMPD). The wind direction data are purchased from weathersource.com. The zip code database is purchased from http://www.zip-codes.com/zip-code-statistics.asp. The pollution data are from the EPA's Air Quality System (AQS). The weather data are from the National Climatic Data Center (NCDC). The sample period is January 2004–December 2010. Full-term low birth weight is represented by a binary variable (1/0), which equals one for the babies with birth weight below 2,500 grams and gestational length greater than or equal to 37 weeks, and zero otherwise. The SO2 (or PM2.5, or NO2) concentrations are computed using the procedures explained in the text, with a 15-mile radius used. The direction-adjusted sulfur dioxide (or nitrogen oxides) emissions (in 1,000 tons) from the power plant are measured by first taking the product of (1) the daily sulfur dioxide (or nitrogen oxides) emissions from the power plant and (2) the cosine function of the difference between daily wind direction (where the wind blows) near the power plant and the New Jersey zip code centroid azimuth (relative to the power plant), and then aggregating the aforementioned product to the zip code-monthly level. The calculation and interpretation of azimuth are given in the text. Weather variables controlled for are monthly high temperature, monthly low temperature, monthly mean temperature, monthly rainfall and monthly snowfall, which are all measured at the zip code level using the procedures explained in the text, with a 15-mile radius used. Linear and quadratic time trend are represented by the linear and quadratic terms of the consecutive integers generated from all year-month pairs (January 2004–December 2010). Zip code fixed effects are used for all specifications. Standard errors (reported in parentheses) are clustered at the zip code level. * Significant at the 10% level; ** Significant at the 5% level; *** Significant at the 1% level.