Association between county-level coal-fired power plant pollution and racial disparities in preterm births from 2000 to 2018

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Abstract

Coal has historically been a primary energy source in the United States (U.S.). The byproducts of coal combustion, such as fine particulate matter (PM$_{2.5}$), have increasingly been associated with adverse birth outcomes. The goal of this study was to leverage the current progressive transition away from coal in the U.S. to assess whether coal PM$_{2.5}$ is associated with preterm birth (PTB) rates and whether this association differs by maternal Black/White race/ethnicity. Using a novel dispersion modeling approach, we estimated PM$_{2.5}$ pollution from coal-fired power plants nationwide at the county-level during the study period (2000–2018). We also obtained county-level PTB rates for non-Hispanic White and non-Hispanic Black mothers. We used a generalized additive mixed model to estimate the relationship between coal PM$_{2.5}$ and PTB rates, overall and stratified by maternal race. We included a natural spline to allow for non-linearity in the concentration–response curve. We observed a positive non-linear relationship between coal PM$_{2.5}$ and PTB rate, which plateaued at higher levels of pollution. We also observed differential associations by maternal race; the association was stronger for White women, especially at higher levels of coal PM$_{2.5}$ (>2.0 $\mu$g m$^{-3}$). Our findings suggest that the transition away from coal may reduce PTB rates in the U.S.

1. Introduction

Coal is the largest fuel source for electricity production worldwide and has historically been a primary energy source in the United States (U.S.) [1]. In recent years, however, competition from low-cost natural gas and the implementation of new regulations have led to increased retirements and retrofits of coal-fired power plants. Coal accounted for 45% of the nation’s electricity generation in 2010, but only 23% by 2019 [1]. In addition, plant owners will likely retire another significant portion of coal-fired capacity by 2025 [2]. The air pollution by-products of this fossil fuel combustion, including particulate matter (PM$_{2.5}$) with an aerodynamic diameter less than or equal to 2.5 $\mu$m (PM$_{2.5}$) and its component sulfate, have increasingly been associated with detrimental health effects [3–5]. Thus, transitions to cleaner sources of energy may lessen exposure to pollutants such as PM$_{2.5}$, and importantly, the health benefits of these transitions may accrue more to those who have been disproportionately impacted. Of particular interest are the associations of PM$_{2.5}$ with adverse health outcomes for pregnant women and developing fetuses, which have health implications across the lifecourse [6–9], and disproportionally and persistently impact Black women in the U.S. [10–12].

Preterm birth (PTB, birth at less than 37 completed weeks of gestation) is a major risk factor for mortality and morbidity later in life. Long-term complications include both physical (respiratory, gastrointestinal, immunologic) and developmental
(cognitive, behavioral, socio-emotional) health problems [13]. PTB has complex and multifactorial causes, with environmental exposures playing a role [14]. Multiple observational studies have shown an association between PM$_{2.5}$ and PTB in the U.S. [15–17]. Trasande et al recently estimated that 3.3% of PTBs nationally—corresponding to 15808 PTBs in 2010—could be attributed to PM$_{2.5}$ [18]. Further, the association between PM$_{2.5}$ exposure and adverse birth outcomes may differ by race/ethnicity and socioeconomic status [19]. In addition to environmental pollutants, social stressors can independently influence health resulting in increased cumulative risk of adverse health outcomes [20]. This may contribute to the notably higher prevalence of PTB among infants born to non-Hispanic Black mothers compared to non-Hispanic White mothers in the U.S. [10, 21].

Few studies have investigated the relative contribution of air pollution to Black–White disparities in PTBs [22], and none have looked at the potential role of energy transitions in reducing disparities in PTBs. To address this gap, we leverage the nation’s decreased reliance on coal as an energy source, as well as a novel ability to estimate exposure to emissions from individual coal-powered electricity-generating units in the U.S. on a small geographical scale. Our exposure metric, hereafter referred to as coal PM$_{2.5}$, was computed with HyADS, a model that employs the HYSPLIT transport and dispersion model to identify exposure patterns from individual sources [23]. The questions that we aimed to answer were: (a) is coal PM$_{2.5}$ associated with PTB rates over time at the county level? (b) Does this association differ between non-Hispanic Black and non-Hispanic White mothers?

2. Methods

2.1. Study population

We obtained annual county-level natality data between 2000 and 2018 from the Centers for Disease Control and Prevention (CDC) WONDER database. We restricted analysis to neonates born to non-Hispanic Black and non-Hispanic White mothers. CDC WONDER includes data on viable births greater than 20 weeks of gestation. It also suppresses PTB counts in counties with less than 100,000 inhabitants and counties where less than nine PTBs occurred in a given year for privacy reasons [24] ($N = 2824$). As previously implemented [25] we additionally restricted our analyses to counties east of 110° longitude (figure S1 (available online at stacks.iop.org/ERL/16/034055/mmedia)) because of the low prevalence of coal facilities in the Western U.S. ($N = 28$). Among remaining counties ($N = 289$), a total of 5491 county-year observations were included in our study. As this study relied on publicly available data [24] it was considered exempt by the Columbia University Institutional Review Board.

2.2. Exposure assessment

For each county-year observation, we estimated annual county-level coal PM$_{2.5}$ exposure using the recently developed HyADS model [25]. HyADS employs the HYSPLIT air parcel transport and dispersion model [26], as well as source-specific information including monthly sulfur dioxide (SO$_2$) emissions and stack height collected by the EPA [27]. We focus on SO$_2$ emissions because of their well-characterized contribution to ambient PM$_{2.5}$ through atmospheric transformation to particulate sulfate [28]. This information allows for the quantification of the impact of emissions from any specific power plant on air quality in each U.S. county. HyADS initially produces a unitless and relative measure of emissions impact, which we calibrated and converted to PM$_{2.5}$ ($\mu$g m$^{-3}$) using region-specific linear relationships with a previously presented observation-adjusted metric for coal exposure [25]. Coal PM$_{2.5}$ concentrations from HyADS are highly correlated with ambient sulfate concentrations, but other PM constituents that are correlated with coal SO$_2$ influence are likely captured in the coal PM$_{2.5}$ metric [23, 25]. The predictive accuracy of HyADS is similar to that of more complex air quality models [23]. HyADS has previously been applied to estimate U.S.-wide health benefits achieved through reduced coal-fired power plant SO$_2$ emissions [29].

2.3. Outcome assessment

For each county-year, we obtained counts of PTB, defined as births before 37 completed weeks of gestation, and all live births separately for non-Hispanic Black and non-Hispanic White neonates. We computed race-specific PTB rates by dividing the race-specific count of PTBs by the race-specific number of live births. We also computed the overall PTB rate, which combines counts for non-Hispanic Black and White neonates for each county-year. All rates were expressed per 100 live births.

2.4. Covariates

The unit of analysis was county-year, so the only potential confounders were factors that could vary between counties and from year to year. Such potential confounders were selected a priori and were adjusted for in models. They included county-year socioeconomic characteristics that were interpolated from the 2000 to 2010 Census as previously implemented [30]: poverty (proportion of individuals living below the federal poverty threshold), educational attainment (proportion of individuals with less than a high school education), median house value, household income, percent non-Hispanic White residents, percent non-Hispanic Black residents, and
rural–urban categorization developed by the U.S. Department of Agriculture [31].

2.5. Statistical analyses
The outcome measure for this analysis was rate ratio of PTB, defined as the ratio of the expected PTB rates at two different points in the distribution of the coal PM$_{2.5}$ concentrations. We first estimated the rate ratio of PTB among infants born to both non-Hispanic White and non-Hispanic Black women combined. We then conducted stratified models by maternal race to estimate race-specific associations.

We modeled the association between coal PM$_{2.5}$ and PTB rate using Poisson generalized additive mixed models with quasi-likelihood to account for potential overdispersion in the outcome. The dependent variable was the count of PTBs and an offset was used to obtain the PTB rate. We first used penalized splines to assess potential deviations from linearity in the concentration–response curve. Penalized splines, however, can be very flexible and result in non-plausible curves. Once non-linearity was detected, therefore, we compared natural spline models with 3 and 4 degrees of freedom. Based on the Akaike Information Criterion, we selected natural spline models by region of the country, such as healthcare provision or climate patterns. To assess the robustness of our findings, we conducted a sensitivity analysis: within state-specific random intercepts to account for factors that might differ by region of the country, such as healthcare provision or climate patterns. To account for potential confounding by factors that vary temporally and covary with the exposure and outcome (i.e. long-term trends), we included a natural spline with 2 degrees of freedom for calendar year.

In a secondary analysis, we stratified models by census region (Northeast, Midwest, and South, figure S1) to account for factors that might differ by region of the country, such as healthcare provision or climate patterns. To assess the robustness of our findings, we conducted a sensitivity analysis: we ran the same models described above further adjusting for PM$_{2.5}$ from sources other than coal-fired power plants, which has consistently been associated with adverse birth outcomes [14]. To generate this PM$_{2.5}$ metric, we obtained publicly available annual surface-level PM$_{2.5}$ concentrations at the county-level predicted from a model that relies on satellite observations, chemical transport modeling, and ground-based monitoring [32]. For each county-year, we then subtracted the annual coal PM$_{2.5}$ from this overall PM$_{2.5}$ concentration to isolate the PM$_{2.5}$ concentration produced by sources other than coal-fired power plants.

Analyses were conducted with R, version 3.6.0 (R Foundation for Statistical Computing, Vienna, Austria).

3. Results
Between 2000 and 2018 the average rate of PTB in counties east of 110° longitude was 13 per 100 live births (table 1). On average, the PTB rate was higher among non-Hispanic Black women than among non-Hispanic White women (17% compared to 11%). This finding of a higher PTB rate among non-Hispanic Black women remained true for each year throughout the study period (figure S2). In addition, figure 1 shows the spatial distribution of PTB at the beginning (2000), midpoint (2009), and endpoint (2018) of the study; the rate of PTBs among Black women was higher than that of White women in most counties included in our analysis (5438 out of 5491 county-years).

Across the study period in all counties, the average coal PM$_{2.5}$ concentration was 1.01 µg m$^{-3}$ (table 1) and was spatially patterned with higher concentrations in the Midwest compared to other areas of the study region (figure 1). Pollution from coal PM$_{2.5}$ consistently decreased over time with all counties experiencing much lower levels in 2018 compared to 2000 (figure S3); the average across counties decreased 89% from 1.75 µg m$^{-3}$ in 2000 to 0.19 µg m$^{-3}$ in 2018 (table S1). The counties included in our analysis were nearly all urban (99.6%) (figure S4).

We observed a non-linear relationship between coal PM$_{2.5}$ and PTBs in the overall population of neonates born to non-Hispanic Black and non-Hispanic White women (figure 2(A)). At lower levels of pollution (<2.0 µg m$^{-3}$), an increase in coal PM$_{2.5}$ was associated with a sharp increase in the risk of preterm birth. Above 2.0 µg m$^{-3}$, the risk of PTB plateaued with increasing concentrations before decreasing at concentrations greater than 2.5 µg m$^{-3}$ (corresponding to the 95th percentile of the coal PM$_{2.5}$ distribution, figure 2(A)). In maternal race-specific stratified models, the exposure-response curve differed for non-Hispanic White women compared to non-Hispanic Black women (figure 2(B)). Below 0.8 µg m$^{-3}$ of coal PM$_{2.5}$ concentration, the association with PTB was positive among non-Hispanic White women but was much weaker than above 0.8 µg m$^{-3}$. Among non-Hispanic Black women, the association was negative (i.e. rates of PTB went down with increasing coal PM$_{2.5}$) until 0.8 µg m$^{-3}$ where the association became positive before plateauing at 2.0 µg m$^{-3}$. At higher levels of pollution (i.e. >2.2 µg m$^{-3}$), the rate of PTB began decreasing for both groups, but in a steeper manner for non-Hispanic Black women.

In secondary regional analysis, the association between coal PM$_{2.5}$ and PTB rate was stronger in the Northeast than it was in the Midwest and the South at higher levels of pollution (>0.8 µg m$^{-3}$). At lower
Table 1. County-level descriptive statistics, 2000–2018, N = 289 counties.

| Characteristic | Mean | SD   | Median | Min  | Max  |
|----------------|------|------|--------|------|------|
| Coal PM$_{2.5}$ (µg m$^{-3}$)$^c$ | 1.01 | 0.79 | 0.80   | 0.02 | 4.38 |
| Total PM$_{2.5}$ (µg m$^{-3}$)$^d$ | 9.94 | 2.38 | 9.65   | 2.56 | 17.88|
| Overall preterm birth rate per 100 live births | 13   | 2    | 12     | 7    | 29   |
| Preterm birth rate per 100 live births among non-Hispanic White women | 11   | 2    | 11     | 6    | 31   |
| Preterm birth rate per 100 live births among non-Hispanic Black women | 17   | 3    | 17     | 6    | 33   |
| Proportion of individuals below poverty level | 0.13 | 0.05 | 0.13   | 0.03 | 0.32 |
| Proportion of individuals with < a high school education | 0.21 | 0.04 | 0.21   | 0.09 | 0.40 |
| Proportion of non-Hispanic White individuals | 0.73 | 0.14 | 0.76   | 0.17 | 0.95 |
| Proportion of non-Hispanic Black individuals | 0.17 | 0.13 | 0.13   | 0.02 | 0.72 |
| Household income ($1000) | 52.60 | 14.37 | 49.00 | 27.00 | 121.00 |
| Median house value ($10,000s) | 17.77 | 10.21 | 15.00 | 5.00 | 100.00 |

$^a$ For counties east of the 110º longitude.
$^b$ Socioeconomic characteristics were interpolated from the 2000 to 2010 Census.
$^c$ Modeled with HyADS.
$^d$ Represents total surface PM$_{2.5}$ from all sources, obtained from the Dalhousie University Atmospheric Composition Analysis Group.

Figure 1. Selected county-level maps of coal PM$_{2.5}$ (column A), preterm birth rate among White women (column B), and preterm birth rate among Black women (column C) at the beginning, midpoint, and endpoint of the study period. Preterm birth rates are expressed per 100 births.
levels, the association was strongest in the Midwest (figure 3). Including non-coal PM$_{2.5}$ in the model did not change results (figure S5).

4. Discussion

We leveraged the transition away from coal-dominated electricity generation in the U.S. to evaluate the association between coal PM$_{2.5}$ and PTB rates over time, first overall and then by non-Hispanic Black and White maternal race/ethnicity. We observed a non-linear relationship between coal PM$_{2.5}$ and PTB; in models that combined both non-Hispanic Black and White births, increasing coal PM$_{2.5}$ was associated with increasing PTB rates at lower levels (<2.0 µg m$^{-3}$), while the association became flat between 2.0 and 2.5 µg m$^{-3}$ and then started decreasing above 2.5 µg m$^{-3}$ of coal PM$_{2.5}$ (corresponding to the 95th percentile of the coal PM$_{2.5}$ distribution). We also observed differential associations by maternal Black–White race/ethnicity, with a slightly stronger relationship between coal PM$_{2.5}$ and PTB among non-Hispanic White women.

Few studies have evaluated the relationship between coal-fired power plants and PTB. The findings of those studies support ours. Ha et al found evidence of increased odds of adverse birth outcomes—including PTB—for women living close to (less than 20 km away from) any power plant compared to women living farther away [33]. In California, Casey et al found that coal and oil power plant retirements were associated with a reduction in PTBs among populations living within 10 km compared to those living 10–20 km away. Neither of these studies explicitly linked coal-fired power plant emission exposures to adverse birth outcomes as we did with HyADS or assessed the relationship between coal PM$_{2.5}$ and PTB while allowing for a non-linear relationship.
In general, studies that have assessed differential associations between air pollution and PTB based on race/ethnicity or socioeconomic status have found stronger associations among non-White racial/ethnic groups and those of lower socioeconomic status [34–36]. Several studies have also pointed to disparities in the distribution of PM$_{2.5}$ emissions from PM-emitting facilities and from U.S. coal-fired power plants specifically, with non-White subgroups being most affected [37, 38]. In light of those findings, we had hypothesized that the association between coal PM$_{2.5}$ and PTB over time would be stronger among non-Hispanic Black women. In fact, our results suggest the opposite at high levels of pollution: a stronger association among non-Hispanic White women. This finding may be due to the restriction of our study population to urban areas and the use of county-level data that may have resulted in exposure misclassification. In urban settings, it is likely that non-Hispanic Black women reside closer to inner cities with other sources of environmental hazards [39, 40], whereas non-Hispanic White women live in suburban contexts closer to coal-fired power plants [41]. Because we relied on county-level data, we could not capture this finer-scale residential spatial distribution of our study participants. This potential explanation, we believe, warrants further research to characterize on a more granular scale the distribution of both source-specific and non-source-specific pollutants according to socioeconomic determinants.

The increased slope at lower concentrations of coal PM$_{2.5}$ agrees with studies that have shown increased risk at lower concentrations of PM$_{2.5}$ [42, 43]. The finding suggests that, while coal has been phased out as a power source in many areas in the U.S. and existing coal power plants are heavily controlled for SO$_2$ emissions, the potential removal of the remaining coal power plants may offer a greater benefit per unit reduction. Other countries that still rely heavily on coal have potential to reduce PTB risk through coal power plant emissions reductions, retirements, and retrofits. The decreased slope at concentrations of coal PM$_{2.5}$ greater than 2.5 µg m$^{-3}$ (corresponding to the 95th percentile of the coal PM$_{2.5}$ distribution) is likely due to data scarcity in that range.

This study had limitations. First, we used an ecological design; given that our unit of analysis was the county, we were unable to characterize intra-county variability and make inferences about individuals within each county. Further, our temporal resolution was calendar-year, which prevented us from accounting for seasonal patterns in the exposure or outcome and may have induced exposure measurement error. For example, births that occurred in January of a given year were assigned the average coal PM$_{2.5}$ concentration of that year. Finally, the analysis was restricted to counties with a minimum count of PTBs and a minimum population density. As a result, we excluded sparsely populated counties, which are mostly rural. This restriction limits the generalizability of our findings.

Strengths of this study include the use of a sophisticated spatio-temporal model to estimate coal PM$_{2.5}$ emitted by specific power plants and the concentration-response modeling choice allowing for non-linearity.

5. Conclusion

We found an association between PM$_{2.5}$ emissions from coal-fired power plants and PTBs over time across 289 U.S. counties. This association was non-linear and appeared to be stronger among non-Hispanic White women in the mostly urban study population. Future research is warranted to characterize exposure distribution on a finer scale according to race/ethnicity and socioeconomic status as well as using birth outcome with improved spatio-temporal resolution. Our findings suggest that the energy transition away from coal may reduce rates of PTB in the U.S.

Data availability statement

The exposure data that support the findings of this study are openly available at the following URL/DOI: https://github.com/misbath/coal-preterm-birth. The outcome data are publicly available through the CDC WONDER database.

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