A Section 508–conformant HTML version of this article
is available at https://doi.org/10.1289/EHP9976.

Evaluating the Impact of the Clean Heat Program on Air Pollution Levels in New York City

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https://doi.org/10.1289/EHP9976

Introduction

Residual heating oil is a class of heavy oil that remains after the lighter components are distilled away from crude oil in the refining process (EIA 2020) and has been linked to adverse health outcomes (Bell et al. 2009). In New York City (NYC), residual heating oil has been identified as a major source of multiple air pollutants, including fine particulate matter [PM ≤ 2.5 μm in aerodynamic diameter ($PM_{2.5}$)] (Clougherty et al. 2010; Kheirbek et al. 2014), sulfur dioxide (SO_2), nitrogen oxides (NO_x) (U.S. EPA 1998), and black carbon (Cornell et al. 2012). Prior to policy implementation, three types of heating oil were used in NYC: heating oil #4, #6, and ultra-low sulfur oil #2. Both #6 and #4 are referred to as residual heating oils, and oil #2, which is the lightest of the three, has been considered a cleaner alternative (Kheirbek et al. 2014). In 2012, NYC established the Clean Heat Program (CHP) to eliminate the use of residual heating oil and move toward cleaner energy forms (Hernández 2016). Here, we have evaluated the CHP outcomes, quantified the CHP-attributable air pollution reductions between 2012 and 2016, and assessed if and how these reductions vary by neighborhood socioeconomic status (SES). We aim to contribute to the knowledge of CHP effects since its implementation, assess relevant equity issues, and inform future policy improvements.

Methods

We conducted analyses at the census-tract level based on the 2010 U.S. Census ($N = 2{,}151$ tracts). Air pollution data were obtained from the New York City Air Community Survey (NYCCAS), which is a large urban air monitoring program that measures levels of numerous air pollutants across NYC. NYCCAS sampling is conducted through various monitoring units placed throughout the city; these data are subsequently included in a land-use regression model to estimate air pollution levels across the city, including locations where no measurements were directly taken (New York City Department of Health 2018). As our pollutants of interest, we selected winter average SO_2 and annual average $PM_{2.5}$ and NO_2 because these pollutants are sensitive to changes to heating oil combustion. Because building fuel conversion began in 2012, we selected 2011 and 2016 to estimate the pre- vs. postpolicy difference in pollutant concentrations. Fuel (heating oils #2, #4, and #6; natural gas; and diesel #2) conversion was quantified by the change of the number of buildings that used a certain fuel type in each census tract. Data were obtained from *a*) Spot the Soot from the NYC CHP and *b*) Benchmark Data provided by the NYC Mayor's Office of Long-Term Planning and Sustainability. We aggregated individual building records by census tract for each fuel type, then calculated the difference in the buildings using each fuel type by census tract between 2012 and 2016. We also considered vehicle miles traveled by buses, cars, and heavy- and medium-duty trucks (from the NYC Department of Transportation) as separate covariates, the average year that the buildings were built in the tract (from the NYC Department of City Planning Property Land Use Tax Lot Output), and median household income (from the U.S. Census Bureau's American Community Survey) as an SES surrogate to account for potential confounding by other policies with similar spatial patterns as CHP.

We used linear regression models and Lagrange multiplier tests to assess spatial autocorrelation and select the appropriate spatial autoregressive model. We used spatial lag models at the census-tract level to investigate the association between fuel conversion and changes in SO_2, $PM_{2.5}$, and NO_2 concentrations while adjusting for covariates. As a sensitivity analysis, we reran models without including the year that the buildings were built or median household income, repeated analyses restricted to those tracts that had at least one building burning fuel #6 in 2012, and additionally adjusted for the change in median household income over the study period.

To examine how SES modified the relationship between fuel conversion and air pollution, we included interaction terms between median household income (quartiles) and fuel conversion away from heating oil #6. All statistical analyses were performed using the R (version 3.5.1; R Development Core Team).

Results and Discussion

Descriptive statistics of all variables are summarized in Table 1. On average, mean (standard deviation) SO_2, $PM_{2.5}$, and NO_2 declined by 4.2 (2.2) ppb, 2.7 (0.4) $\mu g/m^3$), and 4.6 (1.4) ppb, respectively, between 2011 and 2016. Figure 1 shows the estimated reductions in air pollutants per 10 buildings converted from heating oil #6 based on spatial lag models. The reduction in buildings' burning of heating oil #6 was significantly associated with reductions in all three air pollutants. Using the Spot the Soot data set, for every 10 buildings that converted from heating oil #6, we observed a 0.28-ppb [95% confidence interval (CI): 0.22, 0.34], 0.12-$\mu g/m^3$ (95% CI: 0.09, 0.15), and 0.29-ppb (95% CI: 0.17, 0.41) decrease, on average, for SO_2, $PM_{2.5}$, and NO_2, respectively. We also found that conversion away from heating oil #2 was associated with decreases in $PM_{2.5}$ (0.04 $\mu g/m^3$; 95% CI: 0.01, 0.07), and conversion away from

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

Table 1. Descriptive statistics [mean (SD)] across NYC and by quartile of census-tract median household income ($N = 2,151$ census tracts).

Variable	All	Quartile 1	2	3	4
Change in the number of buildings using each type of fuel[a]					
Heating oil					
#2[b]	−0.8 (3.5)	−0.6 (1.4)	−0.5 (1.3)	−0.8 (6.1)	−1.3 (3.1)
#4[b]	0.3 (1.7)	0.0 (1.6)	0.1 (1.4)	0.2 (1.3)	0.8 (2.4)
#6[b]	−2.0 (4.8)	−2.2 (3.7)	−1.2 (3.3)	−1.0 (3.1)	−3.7 (7.4)
Natural gas	3.0 (11.2)	4.1 (9.5)	2.7 (13.9)	2.5 (10.9)	2.5 (10.7)
Diesel #2	0.0 (0.5)	−0.0 (0.2)	0.0 (0.1)	−0.0 (0.0)	0.1 (1.0)
Change in air pollutants					
SO_2 (ppb)	−4.2 (2.2)	−5.2 (2.4)	−4.0 (1.6)	−3.5 (1.4)	−4.3 (2.7)
$PM_{2.5}$ ($\mu g/m^3$)	−2.7 (0.4)	−2.8 (0.4)	−2.6 (0.3)	−2.6 (0.3)	−2.7 (0.4)
NO_2 (ppb)	−4.6 (1.4)	−4.8 (1.0)	−4.5 (0.9)	−4.2 (1.0)	−4.8 (2.2)
Vehicle miles traveled (miles $\times 1,000$)					
Bus	17.3 (36.1)	15.0 (26.9)	11.4 (22.4)	13.1 (28.9)	26.7 (48.9)
Heavy-duty truck	48.0 (127.4)	42.9 (111.8)	30.6 (96.0)	44.4 (102.5)	59.0 (126.8)
Medium-duty truck	63.4 (152.6)	55.5 (129.7)	44.0 (131.3)	57.6 (127.0)	77.6 (137.6)
Car	2,385.3 (5,467.7)	1,619.5 (2,844.2)	1,757.4 (3,433.6)	2,217.0 (4,488.0)	2,925.6 (4,363.5)
Year vehicle was built	1938 (16.1)	1939 (15.8)	1935 (13.3)	1938 (13.8)	1937 (19.2)
Median household income (USD $\times 1,000$)	61.2 (29.9)	29.5 (7.2)	48.6 (4.8)	65.5 (5.5)	101.4 (25.9)

Note: NO_2, nitrogen dioxide; NYC, New York City; $PM_{2.5}$, fine particulate matter (PM $\leq$2.5 μm in aerodynamic diameter); SD, standard deviation; SO_2, sulfur dioxide.
[a]A positive number refers to the number of buildings converting to a certain type of fuel, whereas a negative number refers to the number of buildings converting away from a certain type of fuel.
[b]Data for heating oil #2 come from Benchmark, and data from heating oil #4 and #6 come from Spot the Soot.

heating oil #4 was associated with decreases in SO_2 [0.16 ppb (95% CI: 0.02, 0.30)]. We did not observe any associations for the other fuel types. In sensitivity analyses, we found that removing median household income and building year from the models generally resulted in attenuated effect estimates that remained significant [SO_2: 0.24 ppb (95% CI: 0.19, 0.30); $PM_{2.5}$: 0.04 $\mu g/m^3$ (95% CI: 0.02, 0.05); NO_2: 0.15 ppb (95% CI: 0.09, 0.21)], restricting the analysis to tracts that had at least one building burning heating oil #6 in 2012 resulted in either unchanged or larger effect estimates [SO_2: 0.64 ppb (95% CI: 0.49, 0.79); $PM_{2.5}$: 0.16 $\mu g/m^3$ (95% CI: 0.11, 0.22); NO_2: 0.22 ppb (95% CI: 0.01, 0.43)], and adjusting for change in SES did not change results [SO_2: 0.29 ppb (95% CI: 0.23, 0.35); $PM_{2.5}$: 0.12 $\mu g/m^3$ (95% CI: 0.09, 0.15); NO_2: 0.29 ppb (95% CI: 0.18, 0.41)].

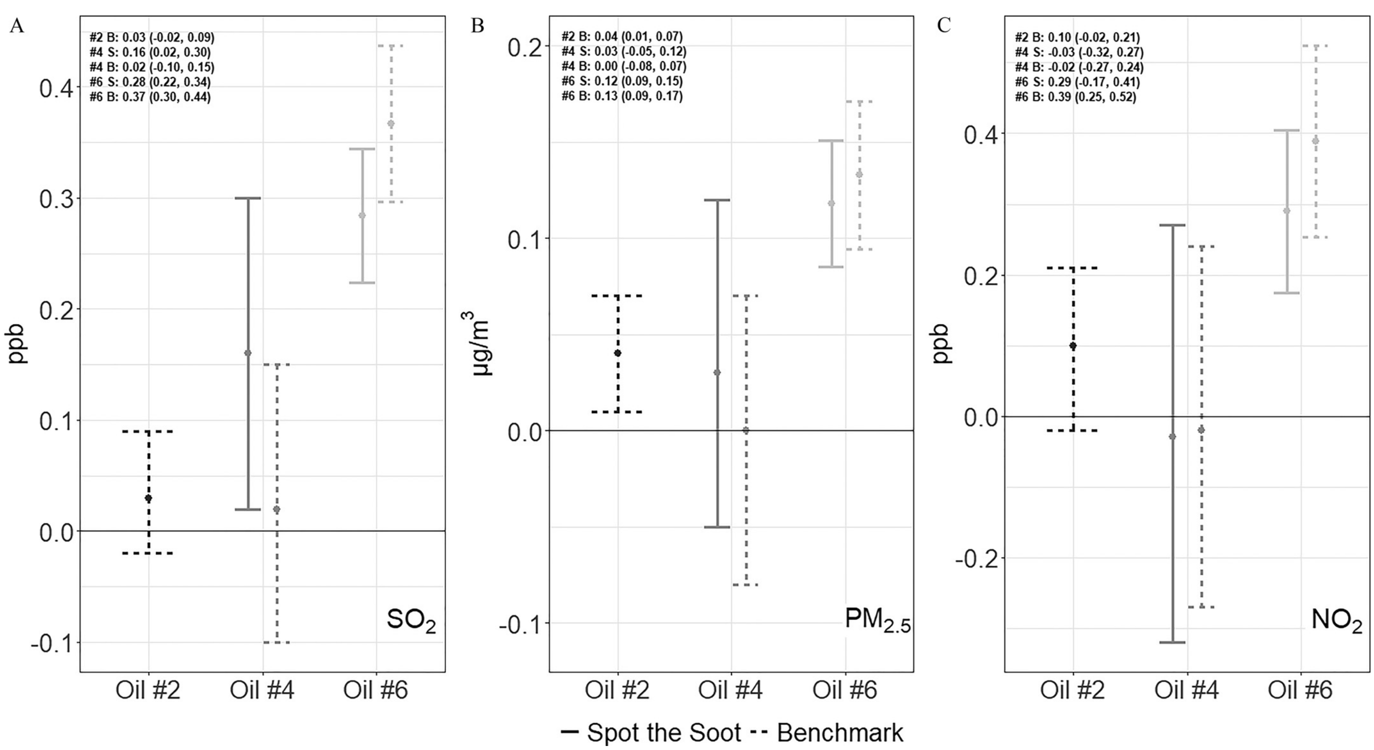

Figure 1. Effect estimates using data from the Spot the Soot (main analysis) and Benchmark data sets based on spatial lag regression models, adjusting for change in natural gas and diesel #2 usage, vehicle miles traveled, and census-tract average building age and median household income. Estimates are presented for heating oils #2, #4, and #6 per 10 buildings converted from each oil type per census tract between 2012 and 2016 for (A) SO_2 (ppb), (B) $PM_{2.5}$ ($\mu g/m^3$), and (C) NO_2 (ppb). Note that oil #2 information was only available from Benchmark. At the top left corner of each panel, we present the numerical estimates and 95% CIs in parentheses. Note: B, Benchmark; CI, confidence interval; NO_2, nitrogen dioxide; $PM_{2.5}$, fine particulate matter (PM $\leq$2.5 μm in aerodynamic diameter); S, Spot the Soot; SO_2, sulfur dioxide.

We assessed potential effect modification by census-tract median household income using income quartiles; we observed the largest effect estimates in the lowest and highest income quartiles. Per 10 buildings converting away from heating oil #6, we observed a 0.38-ppb (95% CI: 0.28, 0.48), 0.21-$\mu g/m^3$ (95% CI: 0.15, 0.27), and 0.30-ppb (95% CI: 0.10, 0.50) decrease in SO_2, $PM_{2.5}$, and NO_2, respectively, in the lowest income quartiles, and a 0.29-ppb (95% CI: 0.14, 0.44), 0.08-$\mu g/m^3$, (95% CI: −0.00, 0.17), and 0.36-ppb (95% CI: 0.06, 0.66) decrease in SO_2, $PM_{2.5}$, and NO_2, respectively, in the highest income quartile.

We observed that the heating oil #6 ban was associated with reductions in air pollution. Conversion away from heating oil #2 was associated with a slight reduction in $PM_{2.5}$ levels but not with any other pollutants. We observed decreases in SO_2 levels associated with heating oil #4, which comprises a mix of oils #2 and #6 combustion and emits 70% of the soot of oil #6 combustion (Urban Green Council 2017). Instead of converting to cleaner fuels, some buildings that burned fuel oil #6 kept their boilers and only switched to fuel oil #4. Based on our results, this intermediate transition step is also partially responsible for reducing air pollution, likely in part due to the architecture of the CHP to also reduce allowable sulfur content for fuel oil #4 (Carrión et al. 2018).

Our study has taken advantage of multiple data sources and provided a framework to evaluate the CHP impact since the time of implementation. By rigorous model diagnostics and selection, we identified and controlled for spatial autocorrelation in the data and adequately accounted for spatial dependence. Our study is limited by the quality of the Benchmark data set, which contained incomplete information. However, we also conducted analyses using information from the Spot the Soot data set, which provides a much more comprehensive coverage of building records for burning and converting from oils #6 and #4. Furthermore, it is particularly promising to see that, regardless of the data set used for analyses, our results are consistent, both in the main and sensitivity analyses. We also acknowledge that although we attempted to account for the influence of factors other than this policy intervention, there may be additional confounders at the census-tract level, and such variables may be partly responsible for the air pollution reductions observed in our analysis.

The CHP has achieved overall success, and it is particularly encouraging to see that the policy was effective for both low- and high-income neighborhoods. However, the heating oil conversion policies were noted to "be designed to reduce emission from a specific sector, not to target sensitive populations" (Kheirbek et al. 2014), and, in fact, low-income communities encountered more barriers in the process of transition, such as lack of knowledge, financial hardship, and uncertainty of the clean fuel market (Carrión et al. 2018). Given the well-established associations of SO_2, $PM_{2.5}$, and NO_2 with numerous adverse health outcomes, the reductions in these air pollutants are likely to result in numerous potential health benefits and improve population health outcomes in NYC.

Acknowledgments

The authors acknowledge S. Johnson, Director of the Air Quality Program at the New York City Department of Health and Mental Hygiene, for her generous feedback on the manuscript. This study was partially supported by the National Institutes of Health/National Institute of Environmental Health Sciences Individual Fellowship Grant (F31 ES029372, to M.Z.H.), Research Project Grant (R01 ES030616, to M.-A.K.), Center Core Grant (P30 ES009089), Training Grant (T32 HD049311), and Specialized Center Grant (P50 ES09600, to F.P.), the U.S. Environmental Protection Agency (RD83615401), the New York Community Trust, and the John and Wendy Neu Family Foundation.

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