Supplementary Information

Improved asthma outcomes observed in the vicinity of coal power plant retirement, retrofit, and conversion to natural gas

Joan A. Casey[1,2], Jason G. Su[1], Lucas R.F. Henneman[4], Corwin Zigler[5], Andreas M. Neophytou[1,6], Ralph Catalano[1], Rahul Gondalia[3], Yu-Ting Chen[7], Leanne Kaye[3], Sarah S. Moyer[7], Veronica Combs[8], Grace Simrall[9], Ted Smith[8], James Sublett[10], Meredith A. Barrett[3]

[1] School of Public Health, University of California, Berkeley, California, USA 94720

[2] Columbia University Mailman School of Public Health, New York, New York, USA 10032

[3] Propeller Health, San Francisco, California, USA 94108

[4] Department of Environmental Health, Harvard TH Chan School of Public Health, Boston, Massachusetts, USA 02115

[5] Department of Statistics and Data Sciences and Department of Women's Health, University of Texas, Austin, Texas, USA

[6] Department of Environmental and Radiological Sciences, Colorado State University, Fort Collins, Colorado, USA 80523

[7] Louisville Metro Department of Public Health and Wellness, Louisville, Kentucky, USA 40202

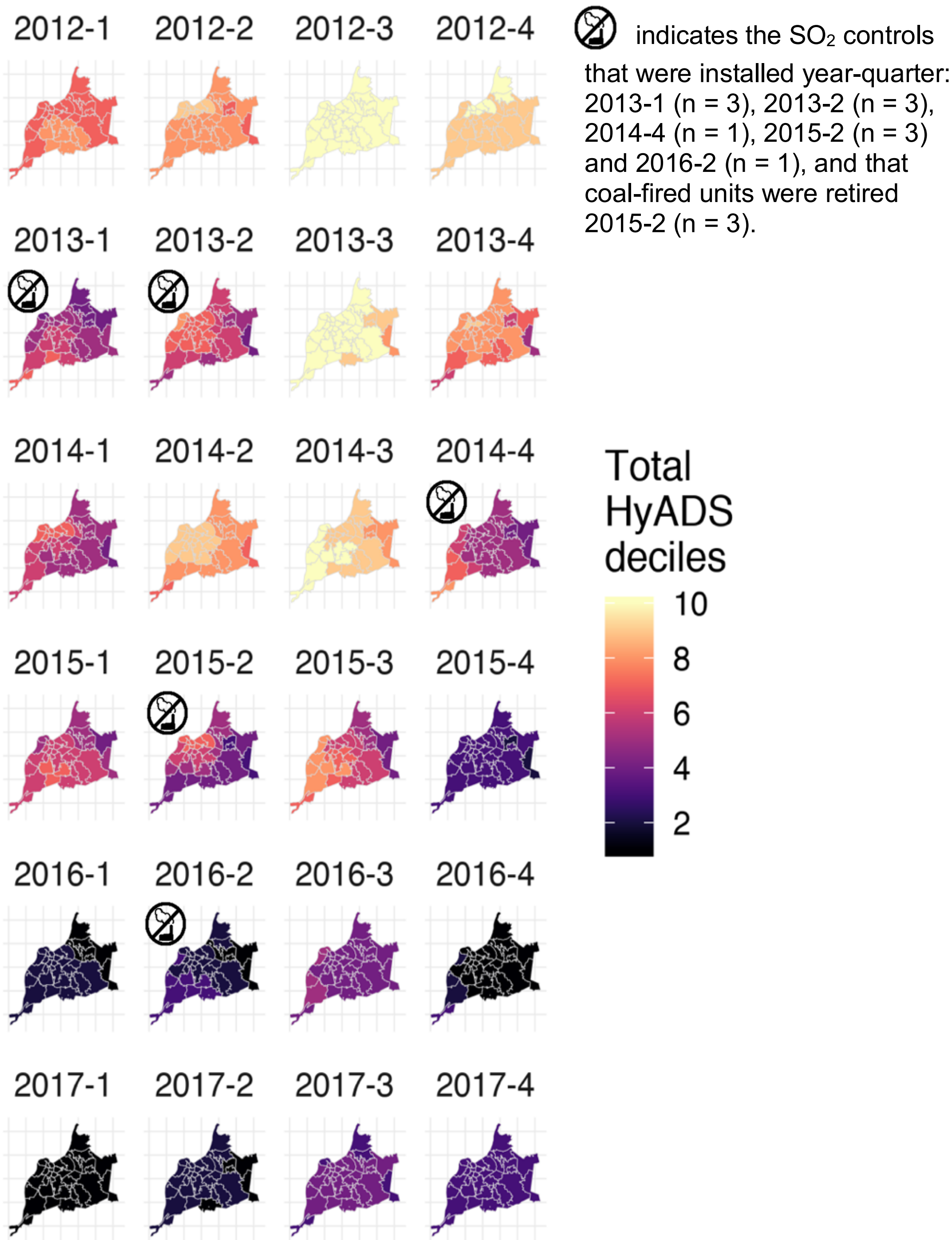
[8] Christina Lee Brown Environment Institute, University of Louisville, Louisville, Kentucky, USA 40202

[9] Louisville Metro Office of Civic Innovation, Louisville, Kentucky, USA 40202

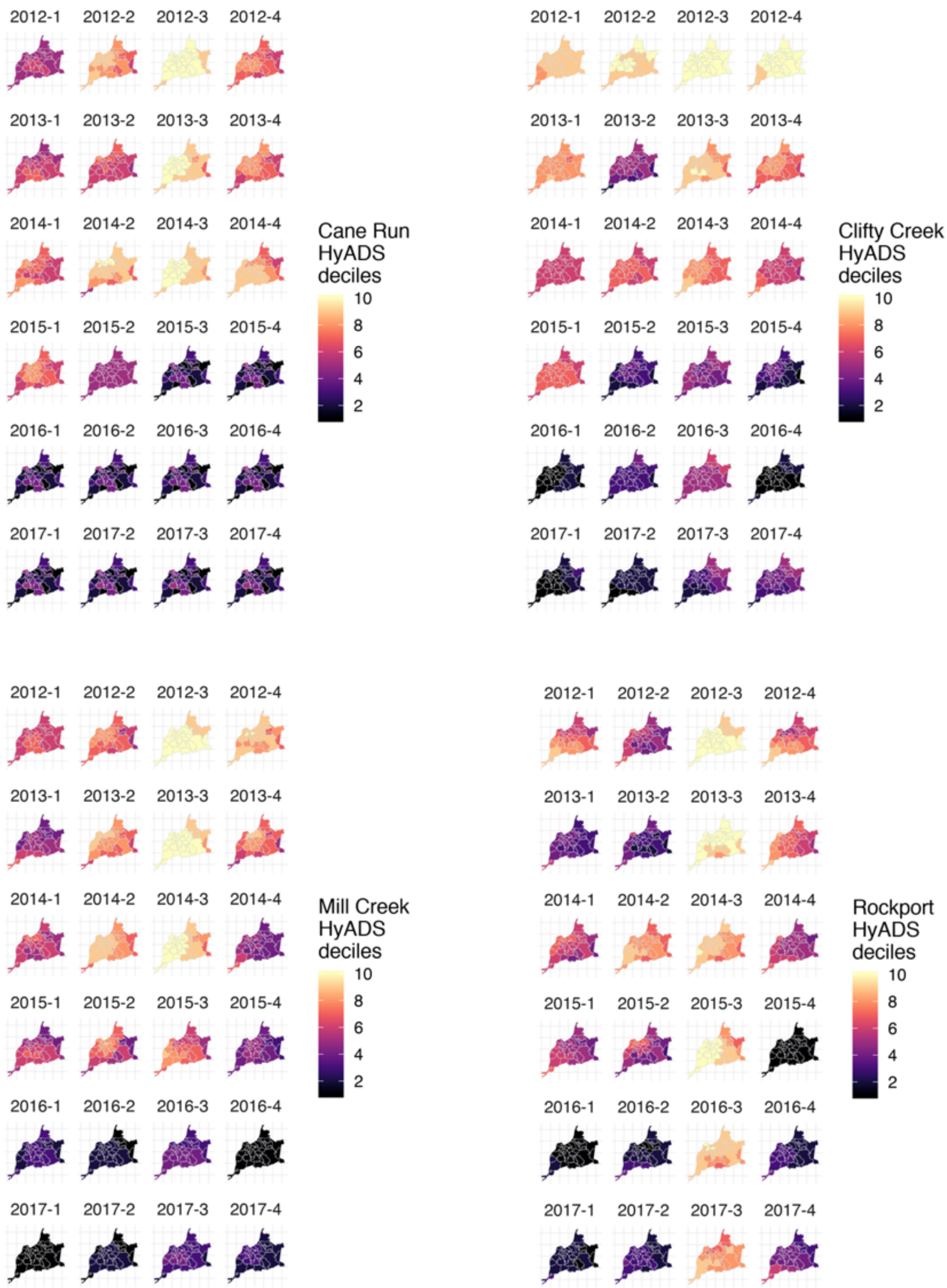
[10] Family Allergy & Asthma, Louisville, Kentucky, USA 40223

SUPPLEMENTARY FIGURES

Supplementary Figure 1: Quarterly mean ZIP code-level HyADS exposure in Jefferson County, Kentucky from 2012–2017. Displayed by ZIP code and decile of total coal-fired power plant air pollution exposure (HyADS) from Cane Run, Clifty Creek, Mill Creek, and Rockport power plants combined. Dates are presented year-quarter.

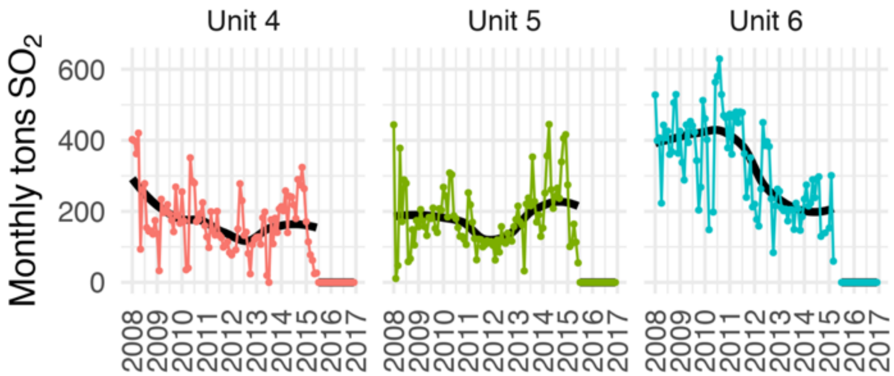


Supplementary Figure 2: Jefferson County, KY ZIP codes and decile of total HyADS exposure. (A) Cane Run; (B) Clifty Creek; (C) Mill Creek; and (D) Rockport power plants, quarterly from 2012–2017. SO_2 controls were installed 2013-1 (n = 3), 2013-2 (n = 3), 2014-4 (n = 1), 2015-2 (n = 3), and 2016-2 (n = 1). Coal-fired units were retired 2-2015 (n = 3).

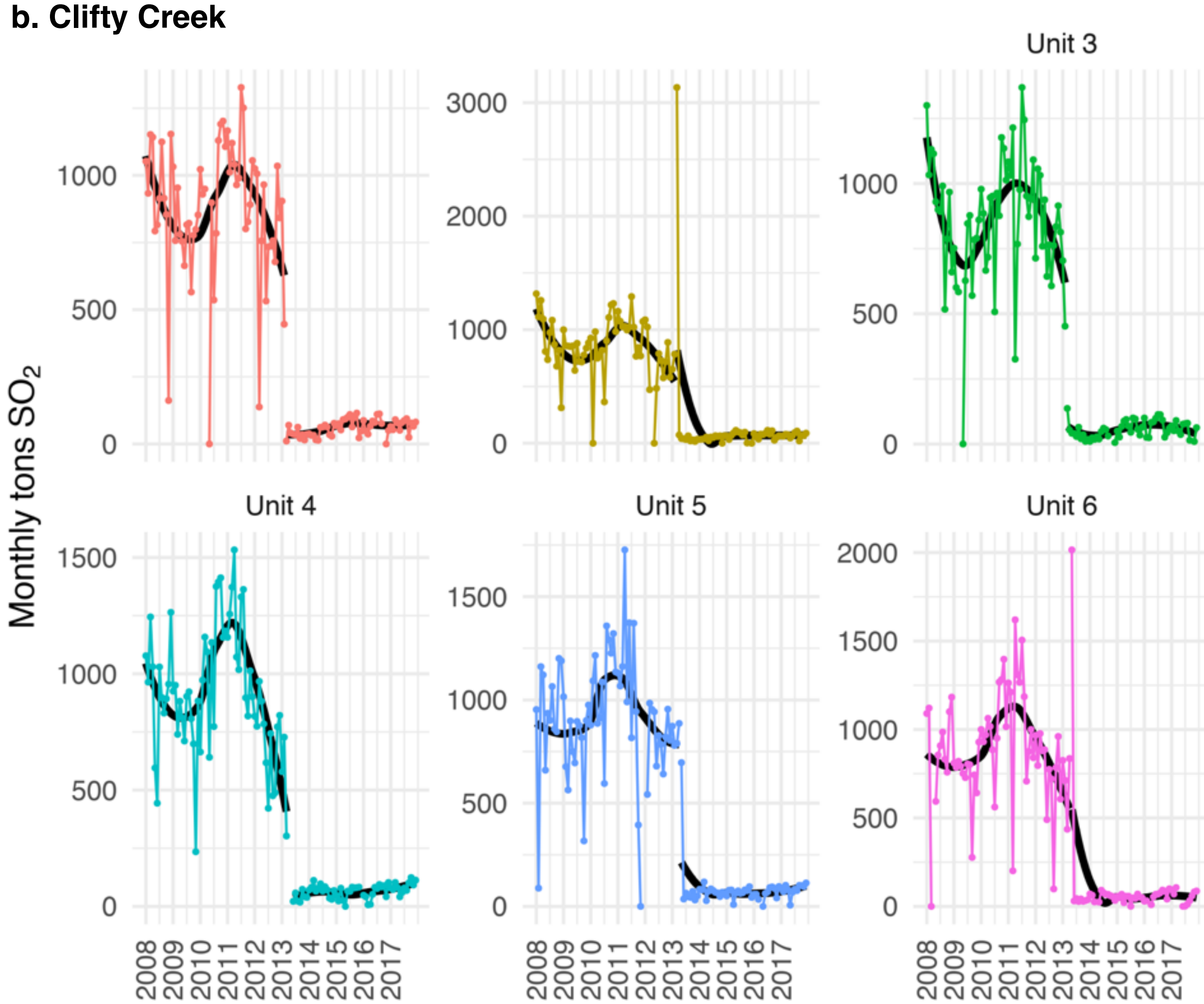


Supplementary Figure 3: **Trends in SO_2 emissions by unit between 2012–2016.** (A) Cane Run; (B) Clifty Creek; (C) Mill Creek; and (D) Rockport power plants. The plots contain discontinuities where a SO_2 control installation or a retirement occurred.

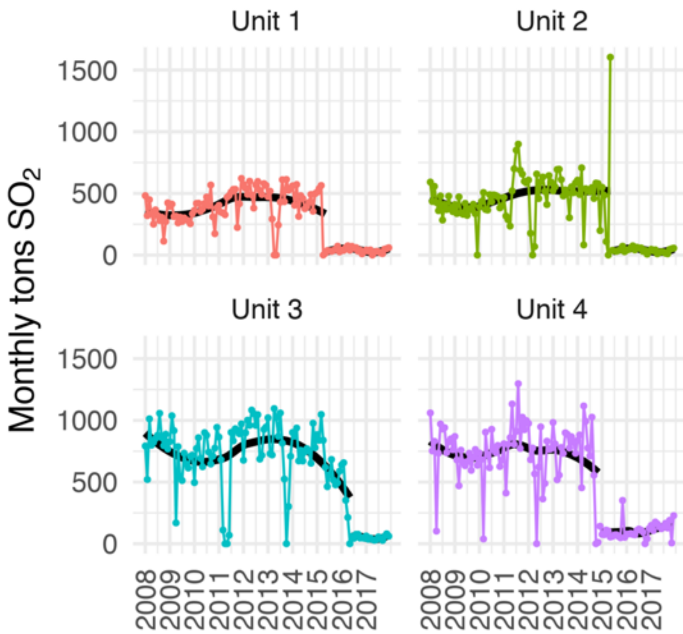
a. Cane Run



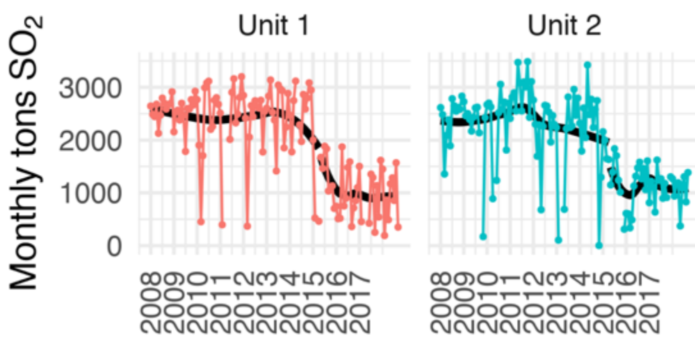
b. Clifty Creek



c. Mill Creek

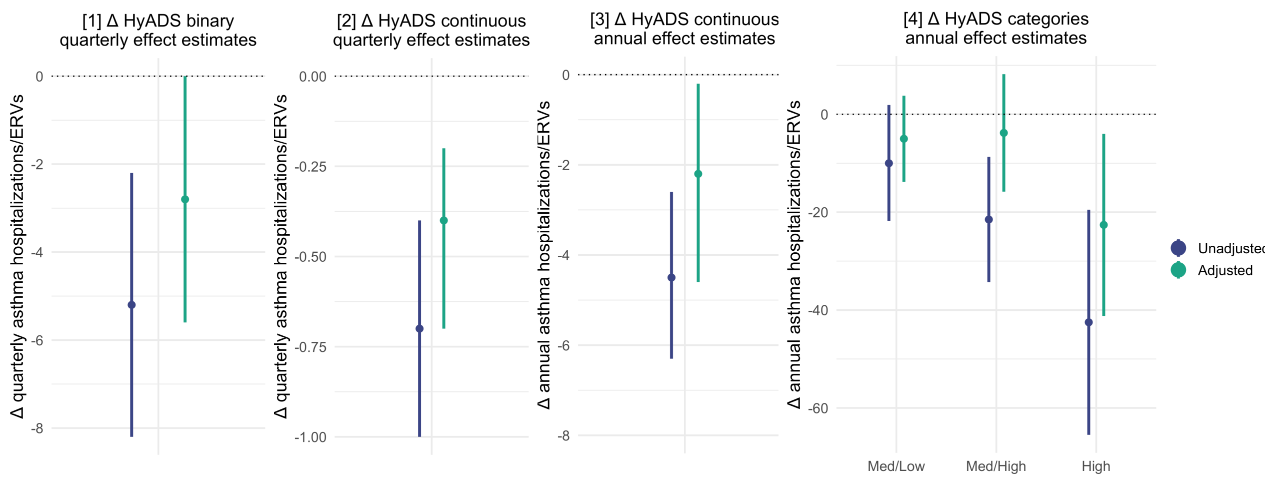


d. Rockport

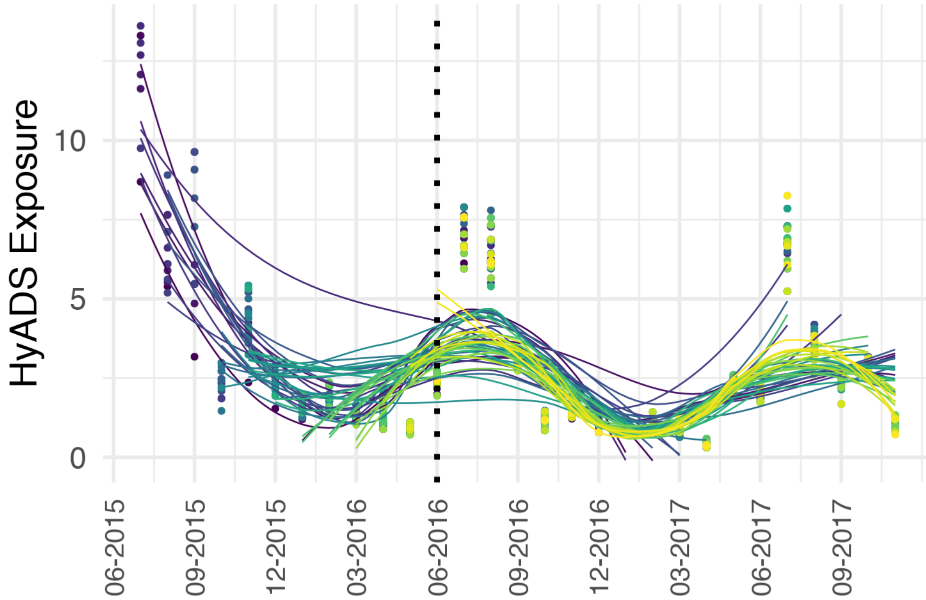


Supplementary Figure 4: ZIP code-level difference-in-differences results from four scenarios estimating the impact of the spring 2015 coal-fired power plant events on counts of ZIP code-level asthma hospitalization/ERVs

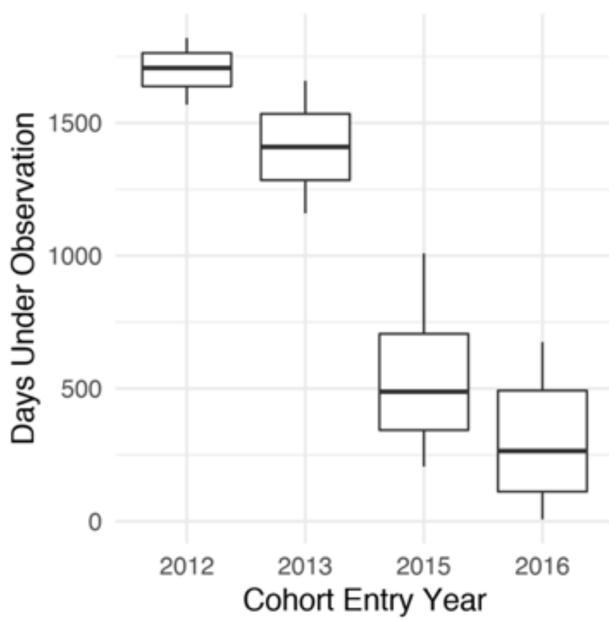
Results from OLS models. Panel [1] shows the estimate from the binary specification of pre-period HyADS (high [≥ 32,500] vs. low [< 32,500]). Panel [2] shows effect estimates per 1000-unit difference in pre-period HyADS. Panels [1] and [2] were adjusted for annual total population, percent non-Hispanic Black individuals, unemployed individuals, and individuals living below the federal poverty threshold, quarterly mean temperature, wind speed, relative humidity, and atmospheric pressure, and included fixed effects for year, quarter, and ZIP code (Equation 3). Panel [3] shows the estimate from a first-difference model regressing change in asthma hospitalizations/ERVs on change in HyADS. The effect estimate can be interpreted per 1000-unit reduction in HyADS from the 4 quarters preceding Q2-2015 to the 4 quarters afterward. Panel [4] shows a similar estimate to panel [3] but uses categories of change in average HyADS: low < 18,000 (reference), medium/low (18,000 to < 22,000), medium/high (22,000 to < 24,000), and high (≥ 24,000). Panels [3] and [4] were adjusted for average ZIP code-level change in total population, uninsured individuals, atmospheric pressure, and temperature from 2014-2 to 2016-2, for example subtracting average temperature in the pre-period from the post-period. They were additionally adjusted for baseline total population (Equation 4). All models used Liang and Zeger cluster-robust standard errors.



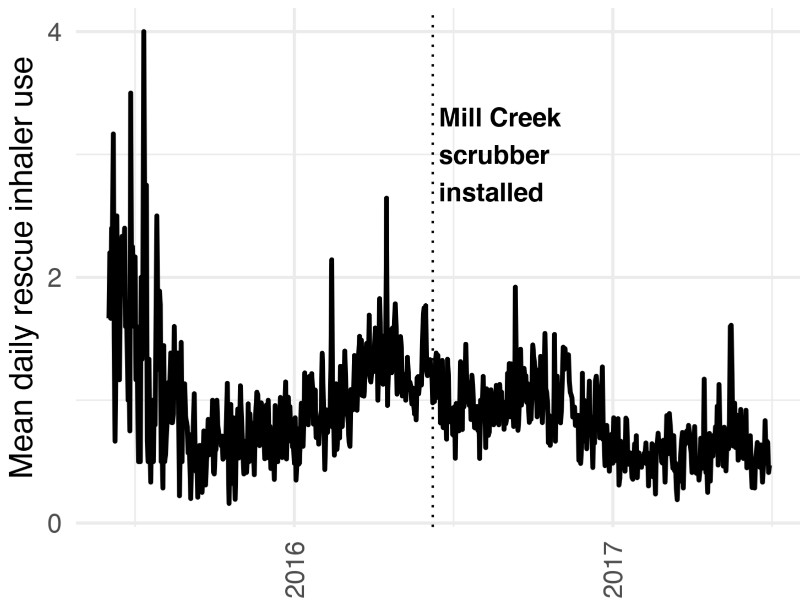
Supplementary Figure 5: **Monthly HyADS exposure (divided by 1000) from June 2015–Dec 2017 for a random sample of study participants (50 of 207 represented).** Points are assigned monthly values and lines are LOESS. Different colors represent different study participants.



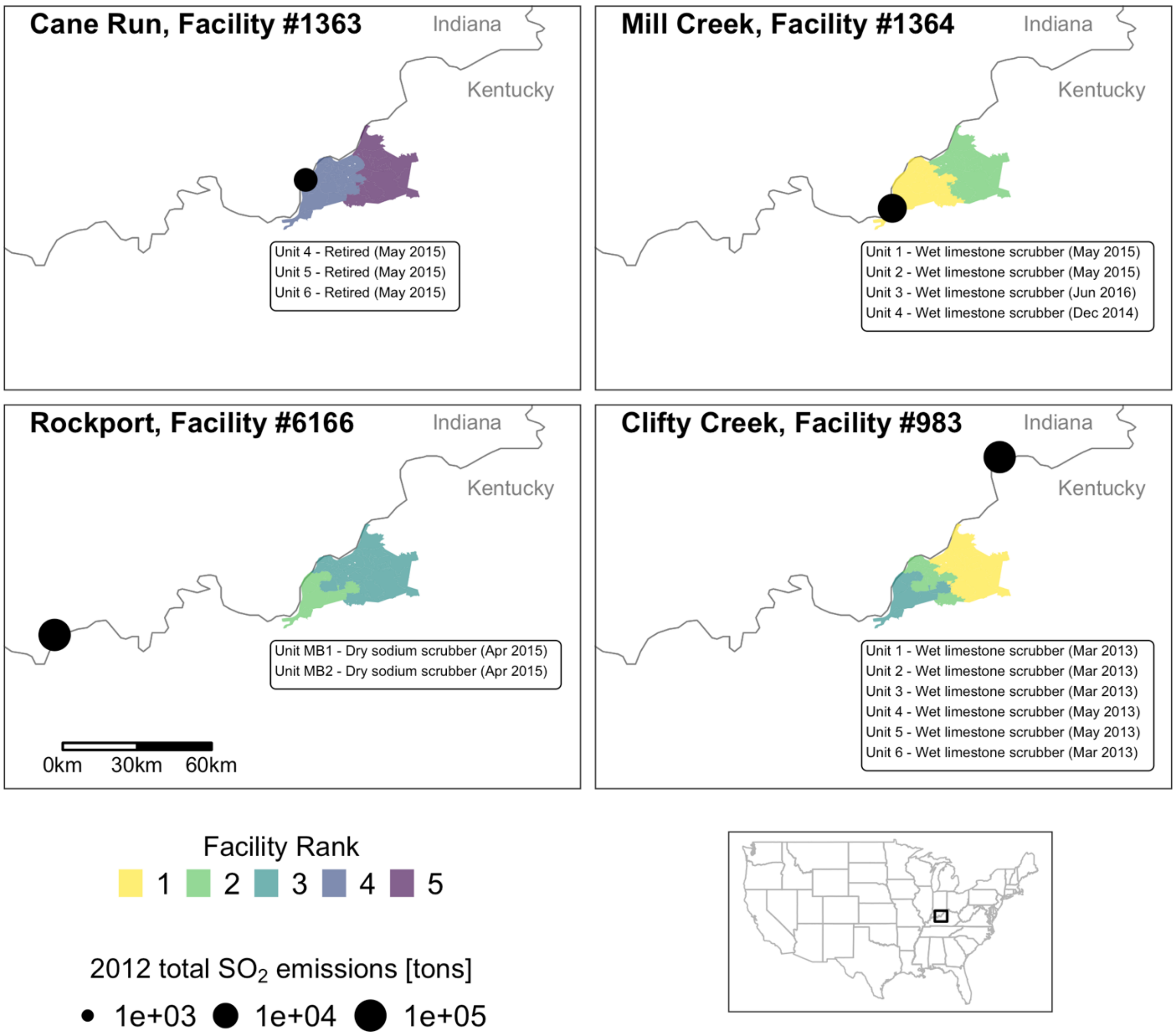
Supplementary Figure 6: Entry year and duration from first to last day under observation for the 207 participants. Data was collected through November 27, 2017.



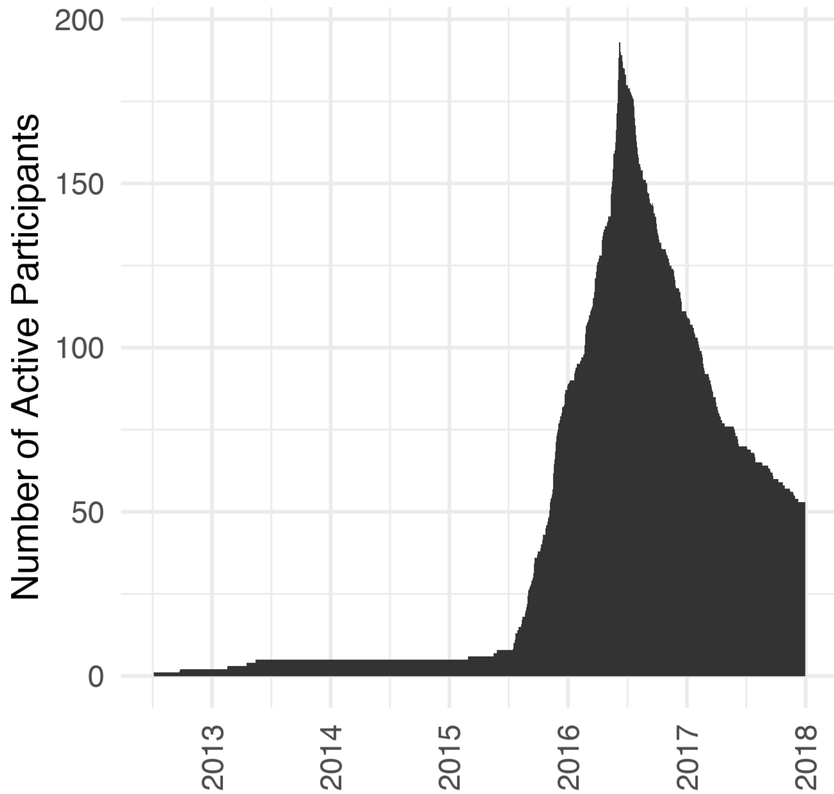
Supplementary Figure 7: Mean daily rescue inhaler use among 207 participants in the AIR Louisville program in Jefferson County, Kentucky, June 8, 2015–June 30, 2017.



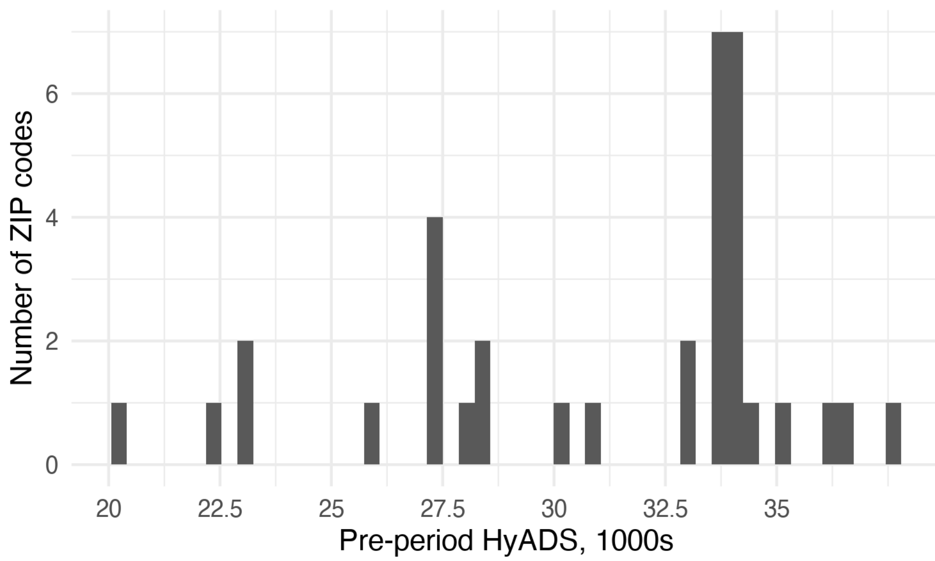
Supplementary Figure 8: Power plant locations, emissions, exposure, and dates of retirements and retrofits. The locations of the four coal-fired power plant facilities, total SO_2 emissions in 2012 (larger graduated black circles indicate higher emissions), and dates of unit retirements and SO_2 control installations. Colors denote coal-fired power plant facility influence on ZIP code-level air pollutant exposures ranked against all U.S. coal power plant facilities in 2012. For example, Mill Creek contributed to poor air quality in the western ZIP codes in Jefferson County more than any other coal facility in the US in 2012. Facility numbers refer to the Air Markets Program Database Facility ID. Unit and facility data downloaded from the U.S. Environmental Protection Agency Air Markets Program.



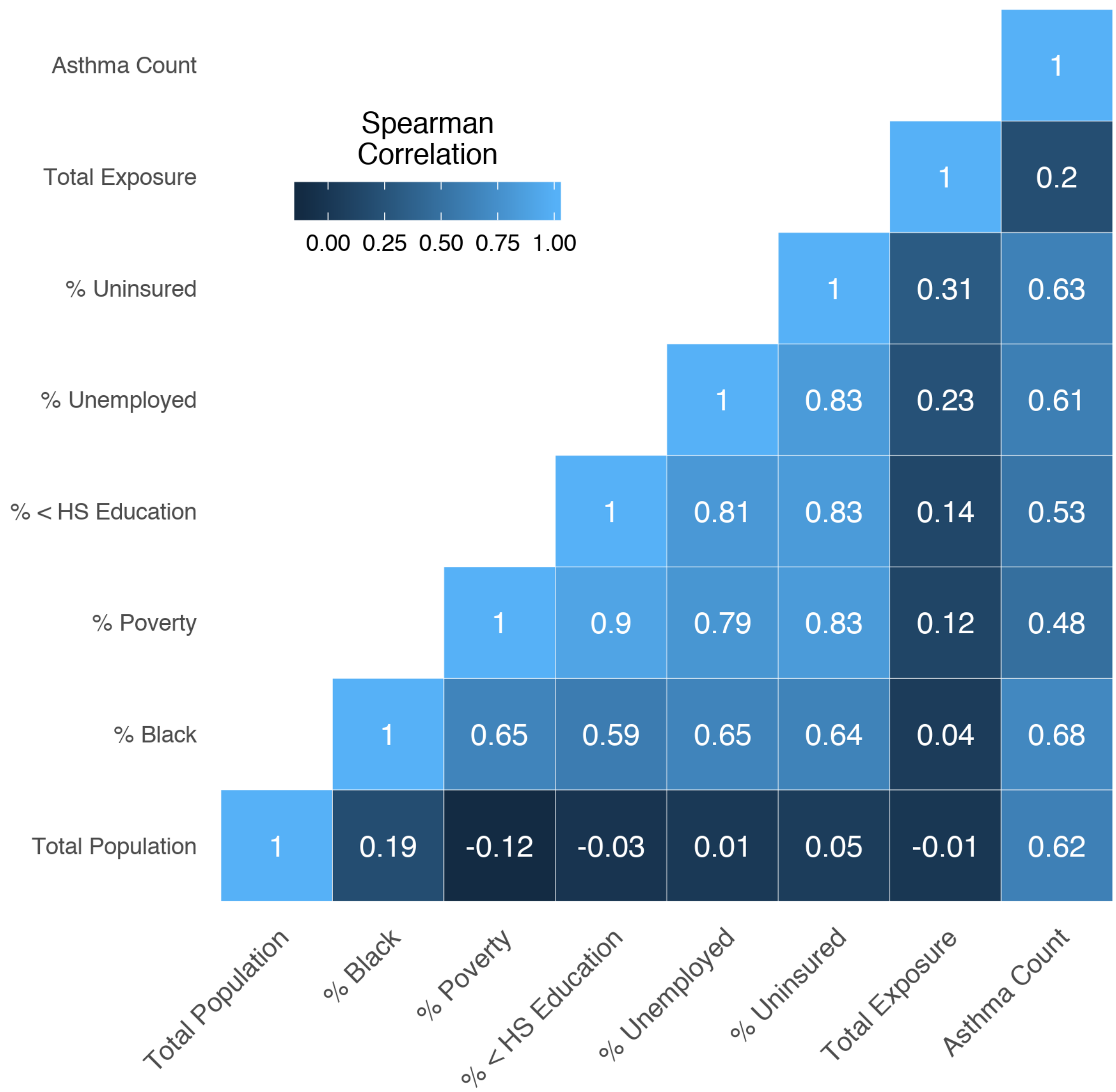
Supplementary Figure 9: The number of participants (of the 207 included in analyses) with rescue inhaler use data each day, June 21, 2012–December 1, 2017. We defined the period of active participation as the days between the participant's first and last sync.



Supplementary Figure 10: Distribution of pre-period average ZIP code-level HyADS (Q2-2014 to Q2-2015). Based on this distribution defined "high" ZIP codes as those with HyADS ≥ 32,500 and the "low" ZIP codes as those with a HyADS < 32,500. The median (IQR) HyADS exposure in the pre-period was 33,540 (27,290, 34,160).



Supplementary Figure 11: Spearman correlation matrix. The matrix includes potential demographic confounding variables, quarterly asthma counts, and quarterly total HyADS exposures at the ZIP code-level, Jefferson County, Kentucky, 2012–2016.



SUPPLEMENTARY TABLES

Supplementary Table 1: ZIP code-level characteristics in Jefferson County, Kentucky, 2012–2016 among ZIP codes with a 2012 population greater than 5.

Demographic characteristics	2012	2013	2014	2015	2016
	Median (IQR)				
Total population	21500 (13727, 30352)	21610 (14426, 30743)	21221 (14229, 31941)	21021 (14353, 32896)	21520 (14194, 33338)
% non-Hispanic Black individuals	9.9 (6.4, 27.0)	10.1 (6.0, 27.3)	10.1 (5.1, 28.7)	10.5 (5.4, 26.1)	10.6 (5.3, 29.4)
% individuals living below the federal poverty threshold	13.5 (6.9, 23.4)	13.0 (7.6, 24.6)	12.5 (7.7, 22.3)	12.4 (7.1, 23.7)	12.1 (6.9, 21.5)
% individuals ≥ 25 years with less than a high school diploma or equivalent	10.8 (4.4, 18.4)	11.3 (4.6, 18.6)	12.5 (3.9, 19.1)	10.9 (4.5, 17.3)	9.5 (3.8, 18.2)
% individuals unemployed	10.0 (5.9, 13.2)	7.5 (5.5, 14.0)	7.9 (5.4, 12.9)	6.9 (4.6, 12.2)	6.3 (4.0, 9.5)
% individuals uninsured	11.9 (7.7, 16.2)	12.8 (7.9, 17.4)	10.7 (7.8, 16.1)	10.3 (6.6, 14.8)	8.4 (5.1, 11.6)
Environmental characteristics					
Quarterly HyADS coal-fired power plant emissions exposure	9867 (7582, 12717)	8713 (5962, 1300)	8892 (6773, 14499)	6795 (3182, 7771)	1420 (1212, 2360)
Temperature, °C	13.9 (8.3, 21.8)	13.3 (6.9, 20.2)	13.9 (6.2, 20.6)	15.9 (8.8, 20.7)	14.5 (8.6, 20.8)
Wind speed, m/s	3.7 (3.2, 4.2)	4.1 (3.0, 4.4)	4.5 (3.3, 4.5)	4.0 (2.9, 4.3)	3.8 (2.9, 4.1)
Relative humidity, %	61.9 (58.4, 65.1)	65.3 (62.5, 66.5)	64.0 (61.1, 65.6)	61.8 (58.1, 62.9)	60.9 (58.0, 64.1)
Atmospheric pressure, mbar	999.8 (998.9-1002.1)	1000.9 (999.5, 1002.8)	1000.8 (999.0, 1002.7)	1000.7 (1000.2, 1003.4)	1001.0 (1000.0, 1001.6)
Heath outcomes					
Asthma hospitalizations/emergency room visits	18 (10, 34)	18 (9, 34)	18 (11, 33)	16 (9, 32)	12 (7, 22)

Demographic characteristics were estimated with 5-year American Community Survey data (i.e., 2008–2012, 2009–2013, 2010–2014, 2011–2015, and 2012–2016), environmental characteristics from the USEPA, and quarterly asthma hospitalization/emergency room visits were provided by the Louisville Metro Department of Public Health and Wellness.

Supplementary Table 2: Difference-in-differences results from four scenarios estimating the impact of the spring 2015 coal-fired power plant events on counts of ZIP code-level asthma hospitalization/ERVs

	Unadjusted DiD estimate	Adjusted DiD estimate
Pre-HyADS binary, quarterly effect estimates		
Baseline population-adjusted[a]	-5.2 (-8.1, -2.3)	-2.8 (-5.6, 0)
Baseline population-weighted[b]	-5.6 (-8.7, -2.5)	-2.7 (-5.8, 0.3)
Pre-HyADS continuous, quarterly effect estimates		
Baseline population-adjusted[a]	-0.7 (-1.0, -0.4)	-0.4 (-0.7, -0.2)
Baseline population-weighted[b]	-0.7 (-1.1, -0.4)	-0.4 (-0.8, -0.1)
∆ HyADS continuous, annual effect estimates		
Baseline population-adjusted[a]	-4.5 (-6.3, -2.6)	-2.2 (-4.6, 0.2)
Baseline population-weighted[b]	-4.8 (-7.0, -2.6)	-2.4 (-5.3, -0.6)
∆ HyADS categories, annual effect estimates		
Baseline population-adjusted[a]		
Category 2 vs. Category 1	-10.0 (-21.8, 1.9)	-5.0 (-13.8, 3.8)
Category 3 vs. Category 1	-21.5 (-34.3, -8.7)	-3.8 (-15.8, 8.2)
Category 4 vs. Category 1	-42.5 (-65.5, -19.5)	-22.6 (-41.2, -4.0)
Baseline population-weighted[b]		
Category 2 vs. Category 1	-7.4 (-23.5, 8.8)	-5.3 (-13.7, 3.0)
Category 3 vs. Category 1	-18.7 (-37.4, 0.1)	-3.9 (-16.7, 9.0)
Category 4 vs. Category 1	-41.2 (-63.9, -37.4)	-24.2 (-42.2, -6.3)

Abbreviations: ERVs, emergency room visits

Row [1] shows the estimate from the binary specification of pre-period HyADS (high [≥ 32,500] vs. low [< 32,500]). Row [2] shows effect estimates per 1000-unit difference in pre-period HyADS. Panels [1] and [2] were adjusted for annual total population, percent non-Hispanic Black individuals, unemployed individuals, and individuals living below the federal poverty threshold, quarterly mean temperature, wind speed, relative humidity, and atmospheric pressure, and included fixed effects for year, quarter, and ZIP code (Equation 3). Panel [3] shows the estimate from a first-difference model regressing change in asthma hospitalizations/ERVs on change in HyADS. The effect estimate can be interpreted per 1000-unit reduction in HyADS from the 4 quarters preceding Q2-2015 to the 4 quarters afterward. Row 4 shows a similar estimate to Row 3 but uses categories of change in average HyADS: low < 18,000 (reference), medium/low (18,000 to < 22,000), medium/high (22,000 to < 24,000), and high (≥ 24,000). Rows [3] and [4] were adjusted for average ZIP code-level change in total population, uninsured individuals, atmospheric pressure, and temperature from 2014-2 to 2016-2, for example subtracting average temperature in the pre-period from the post-period. They were additionally adjusted for baseline total population (Equation 4). All models used Liang and Zeger cluster-robust standard errors.

[a] Model was adjusted for baseline (2014) total population at the ZIP code-level

[b] Model was not adjusted for baseline (2014) total population at the ZIP code-level, but rather weighted by the ZIP code-level population divided by the overall study population.

Supplementary Table 3: Descriptive characteristics of the 207 study participants in Jefferson County, Kentucky, 2012–2017

Characteristic	
Female sex, n (%)	139 (67)
Race/ethnicity, n (%)	
Asian	1 (0.5)
Black/African American	49 (24)
Hispanic	2 (1)
Native American	2 (1)
White	131 (63)
Not reported	22 (11)
Age, y	44.7 (17.6)
Days under observation	602 (321)
Daily rescue inhaler use	1.0 (1.5)
Monthly rescue inhaler use	25 (40)
Area-level risk factors	
Community social vulnerability index[a]	0.42 (0.26)
Daily environmental measures	
Temperature, °C	16.4 (2.7)
Wind speed, m/s	6.6 (1.1)
Relative humidity, %	65 (3)
Atmospheric pressure, mbar	999.0 (1.4)
Grass pollen count per m^3	0.9 (0.5)
Tree pollen count per m^3	18.6 (10.4)
Weed pollen count per m^3	2.1 (1.1)
Mold count per m^3	1382 (248)
Quarterly HyADS exposure, median (IQR)	1915 (1172, 3050)

Data are mean (SD) unless otherwise specified.

[a] Based on 15 factors grouped into 4 themes: socioeconomic status; household composition; race/ethnicity/language; and housing/transportation at the census tract level. It ranges from 0 to 1; where 1 corresponds to the most vulnerable communities.

Supplementary Table 4: Associations of the Mill Creek SO_2 scrubber installation on June 8, 2016 and individual-level daily SABA use (any vs. no and high [≥4 uses/day vs. less]) among 207 participants in Jefferson County, Kentucky, 2012–2017.

Coefficient	Adjusted RR (95% CI)	Description
Any versus no SABA use		
Scrubber installation	1.02 (0.90, 1.15)	Level shift
Time x scrubber installation	0.83 (0.71, 0.97)	Slope change
≥4 SABA uses/day vs. less		
Scrubber installation	0.68 (0.45, 1.02)	Level shift
Time x scrubber installation	0.94 (0.90, 1.00)	Slope change

Results from a conditional binomial case interrupted time-series model. Effect estimates should be interpreted within-participant. Models were adjusted for temperature, humidity, windspeed, atmospheric pressure, ambient pollen (grass, tree, and weed), mold counts, and long-term and seasonal trends.

Supplementary Table 5: Roadmap for study analyses

Question	Dataset(s)	Statistical analysis	Results
ZIP code-level quarterly data from 2012–2016 in 35 ZIP codes			
1. Were coal-fired power plant energy transitions associated with reduced emissions and HyADS exposures?	Quarterly HyADS exposure model	Descriptive analyses and OLS model (Equation 1)	Figure 2, Supplementary Figures 1-3, Table 1
2. Were coal-fired power plant events associated with changes in asthma-related hospitalizations or ED visits?	Quarterly HyADS exposure model and Jefferson county asthma counts	Poisson model, difference-in-differences, and first-difference analyses (Equations 2-4)	Table 2, Figures 3 and 4, Supplementary Figure 4, Supplementary Table 2
Individual-level daily latitude-longitude data on 207 participants from 2015–2017			
3. Was the Mill Creek unit 3 scrubber installation in 2016 associated with reduced emissions and HyADS exposures?	Monthly HyADS exposure model	Descriptive analyses and OLS model	Figure 5, Supplementary Figures 2 and 3
4. Was the Mill Creek unit 3 scrubber installation in 2016 associated with rescue inhaler use?	Monthly HyADS exposure model and AIR Louisville cohort	Interrupted case time-series conditional Poisson model (Equation 5)	Figure 6, Supplementary Table 4

SUPPLEMENTARY NOTES

Supplementary Note 1. HyADS model

Running HyADS entailed four steps as described in Henneman et al. 2019.[1] First, for every day during a specified year, 100 HYSPLIT dispersion trajectories were initiated four times daily for each unit and tracked for 10 days. Second, the resulting hourly air parcel locations were pruned by removing those in hours 0 and 1, those that reach a height of 0, and those at altitudes above the planetary boundary layer. Third, the remaining parcels were allocated to ZIP codes by month, creating monthly source-receptor matrices. Finally, values in these matrices were weighted by monthly unit-specific SO_2 emissions, yielding unitless exposure to coal SO_2 emissions, hereafter referred to as HyADS exposure. This process provides straightforward lookup tables of each coal unit's influence on each ZIP code in the U.S.

Supplementary Note 2. First difference model – alternative specification and covariate selection

In a secondary analysis, we used a first-difference design.[2] We specified two versions of first-difference models. In the first, an annual-level model, we evaluated the relationship between the pre-post change in HyADS and pre-post change in ZIP code-level hospitalization/ERVs. This model took the form:

$$\Delta Asthma_{pr} = \beta_0 + \beta_1 \Delta HyADS_{pr} + \Delta\lambda_{pr} + \Delta\theta_{pr} + \varepsilon_{pr} \quad (4)$$

where $\Delta Asthma_{pr}$ represents the differences between counts of ZIP code-level asthma hospitalization/ERVs in the year prior to Q2-2015 and the year after Q2-2015 and $\Delta HyADS_{pr}$ represents the ZIP code-level difference in HyADS exposure to the three facilities of interest from the year prior to Q2-2015 to the year after Q2-2015. We took differences in meteorological and demographic variables ($\Delta\lambda_{pr}$ and $\Delta\theta_{pr}$) by subtracting the average value between Q2-2014 and Q1-2015 from the average value between Q3-2015 and Q2-2016. After evaluating the correlation structure of the meteorological and demographic change variables with each other, the exposure, and outcome (**Supplementary Figure 11**), we adjusted only for change in temperature, atmospheric pressure, population, and uninsured status. We selected these variables due to high correlation (Spearman $\rho > 0.65$) between relative humidity, wind speed, and temperature differences and the minimal correlation (Spearman $\rho < 0.25$) between change in poverty and proportion non-Hispanic Black race/ethnicity individuals and exposure and outcome. In a separate model, we allowed for non-linearity in the association between $\Delta HyADS_{pr}$ and $\Delta asthma_{pr}$ by specifying categories of $\Delta HyADS_{pr}$. Based on the distribution of change in HyADS (**Supplementary Figure 2**), we selected four categories (the reference group [< 18,000], medium/low [18,000 to < 22,000], medium/high [22,000 to < 24,000], and high [≥ 24,000]). In both the difference-in-differences and first-difference models, we accounted for correlation of exposure assignment within ZIP codes using Liang and Zeger cluster-robust standard errors.[3]

SUPPLEMENTARY REFERENCES

1 Henneman, L. R. F., Choirat, C., Ivey, C. E., Cummiskey, K. & Zigler, C. M. Characterizing population exposure to coal emissions sources in the United States using the HyADS model. *Atmos Environ* **203**, 271-280 (2019).

2 Pope, C. A., 3rd, Ezzati, M. & Dockery, D. W. Fine-particulate air pollution and life expectancy in the United States. *N Engl J Med* **360**, 376-386, doi:10.1056/NEJMsa0805646 (2009).

3 Abadie, A., Athey, S., Imbens, G. W. & Wooldridge, J. *When should you adjust standard errors for clustering? NBER*, <https://www.nber.org/papers/w24003> (2017).