1 **Disparities in air pollution exposure in the United States by race-ethnicity and**
2 **income, 1990 – 2010**

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Abstract

Background: Few studies have investigated air pollution exposure disparities by race-ethnicity and income across criteria air pollutants, locations, or over time in the United States (US).

Objectives: To quantify exposure disparities by race-ethnicity and income, throughout the contiguous US, for outdoor concentrations of six criteria air pollutants, during 1990 to 2010.

Methods: We quantified exposure disparities among four racial-ethnic groups (White, Black, Hispanic, Asian) and by income for multiple spatial units (contiguous US, states, urban vs. rural areas) and years (1990, 2000, 2010) for six criteria air pollutants: carbon monoxide [CO], nitrogen dioxide [NO₂], ozone [O₃], particulate matter [PM_{2.5} and PM₁₀], sulfur dioxide [SO₂]. We used census data for demographic information and a national empirical model for estimated ambient air pollution levels.

Results: For all three census years and all six pollutants, the racial-ethnic group with the highest national average exposure was a minority group. In 2010, the exposure gap between the racial-ethnic group with the highest versus lowest average exposure was largest for NO₂ (64%, 4.6 ppb), smallest for O₃ (4%, 1.6 ppb), and intermediate (13%-21%) for remaining pollutants. Averaged across pollutants in 2010, exposures were at least 5% higher than average for non-Hispanic Black and Hispanic populations in most states (~73% and ~57% of US states, respectively), for non-Hispanic Asian populations in many states (~35%), and for non-Hispanic White populations in no states. National average racial-ethnic exposure disparities were, on average across pollutants, ~six times larger than income-based exposure disparities. From 1990 to 2010, national average racial-ethnic exposure disparities declined 69% on average across pollutants.

Discussion: As air pollution concentrations declined during 1990 to 2010, racial-ethnic exposure disparities also declined. However, in 2010, racial-ethnic exposure disparities remained across income levels, in urban and rural areas, and in all states, for multiple pollutants.

Introduction

Air pollution is associated with ~100,000 annual premature deaths in the United States (US) (Stanaway et al. 2018) and is linked to cardiovascular disease, respiratory disease, cancers, adverse birth outcomes, cognitive decline, and other health impacts (Cohen et al. 2017; Darrow et al. 2019; Lelieveld et al. 2015; Paul et al. 2019; Pope et al. 2009; Rivas et al. 2019; Stieb et al. 2012; Underwood 2017). Air pollution, and its associated health impacts, is not equitably distributed by race-ethnicity or income. Previous research has documented higher-than-average air pollution exposures for racial-ethnic minorities and lower-income populations in the US (Brulle and Pellow 2006; Evans and Kantrowitz 2002; Mohai et al. 2009), leading to disparities in attributable health impacts (Bowe et al. 2019; Fann et al. 2019; Gee and Payne-Sturges 2004). Most investigations of disparities in air pollution exposure involve a single pollutant, location, and/or time-point (Hajat et al. 2015; Marshall et al. 2014). Evidence from more comprehensive investigations suggests that exposure disparities by race-ethnicity and/or income can vary by pollutant (Rosofsky et al. 2018), location (e.g., by state (Bullock et al. 2018; Salazar et al. 2019), urbanicity (Mikati et al. 2018), metropolitan area (Zwickl et al. 2014; Downey et al. 2008)), and time-point (Ard 2015; Clark et al. 2017; Kravitz-Wirtz et al. 2016; Colmer et al. 2020). However, broad patterns in exposure disparities have not yet been investigated, using consistent methods, across pollutants, locations, and time-points, for the national population.

The objective of our research was to comprehensively and consistently investigate disparities in exposure to Environmental Protection Agency (EPA) criteria air pollutants for the two decades following the 1990 Clean Air Act Amendments in the US. Specifically, we investigated the following questions regarding disparities in exposure to six criteria air pollutants: (1) How do exposures vary by race-ethnicity and income? (2) How do racial-ethnic exposure disparities vary by pollutant? (3) How do racial-ethnic exposure disparities vary by location (state, urban vs. rural areas)? (4) How have racial-ethnic exposure disparities changed over time? To address these questions, we combined demographic data from the US Census (Manson et al. 2019) with predictions of outdoor average levels of six criteria air pollutants from a publicly-available national empirical model derived from satellite, measurement and other types of data (Kim et al. 2020) at the spatial scale of census block groups and census tracts. We then analyzed disparities in exposure to six criteria air pollutants (all criteria air pollutants except lead [Pb]; i.e., carbon monoxide [CO], nitrogen dioxide [NO₂], ozone [O₃], fine and coarse particulate matter [PM_{2.5}, PM₁₀], and sulfur dioxide [SO₂]) by race-ethnicity (four racial-ethnic groups: white, Black, Hispanic, Asian) and income (16 household income categories) across time-points (decennial census years: 1990, 2000, and 2010) and spatial units (contiguous US, state, urban vs. rural areas).

Methods

Demographic and Air Pollution Datasets

We obtained demographic data (i.e., population estimates by race-ethnicity, household income, and household income disaggregated by race-ethnicity) and map boundaries (e.g., states, census tracts, and census block groups) for the contiguous US from the 1990, 2000, and 2010 decennial census from the IPUMS National Historic Geographic Information System (NHGIS) (Manson et al. 2019).

NHGIS provides, for each census block group, and for 1990, 2000, and 2010 (standardized to 2010 spatial boundaries), population estimates for six census racial groups: (i) White alone, (ii) Black or African American alone, (iii) American Indian and Alaska Native

alone, (iv) Asian and Pacific Islander alone, (v) some other race alone, and (vi) two or more races. NHGIS reports population estimates for two census ethnic groups: (i) Hispanic or Latino and (ii) not Hispanic or Latino. Thus, there are 12 racial-ethnic groups in NHGIS (six racial groups, two ethnic groups). Our main analyses here regarding racial-ethnic exposure disparities included the four largest racial-ethnic groups, which in total covered 307 million people (97.2% of the population) in the contiguous US in 2010: (i) non-Hispanic White alone (64% of the population; hereafter, “non-Hispanic White”), (ii) Hispanic of any race(s) (16%; hereafter, “Hispanic”), (iii) non-Hispanic Black or African Americans alone (12%; hereafter, “non-Hispanic Black”), and (iv) non-Hispanic Asian and Pacific Islander alone (4.6%; hereafter, “non-Hispanic Asian”).

For analyses by income in 2010, we used 2010 NHGIS household income estimates. For each block group, NHGIS reports the number of households in 16 annual household income categories (total covered in 2010: 114 million households): <10k, 10k–15k, 15k–20k, 20k–25k, 25k–30k, 30k–35k, 35k–40k, 40k–45k, 45k–50k, 50k–60k, 60k–75k, 75k–100k, 100k–125k, 125k–150k, 150k–200k, and >200k (2010 inflation-adjusted US dollars).

For analyses by income disaggregated by race-ethnicity in 2010, we used 2010 NHGIS data. For each census tract, NHGIS reports the number of census householders in each of the 16 census income categories, disaggregated in eight census racial and/or ethnic groups: (i) not Hispanic or Latino White alone, (ii) Black or African American alone, (iii) American Indian and Alaska Native alone, (iv) Asian alone, (v) Native Hawaiian and Other Pacific Islander alone, (vi) some other race alone, (vii) two or more races, and (viii) Hispanic or Latino. To best match demographic variables used in race-ethnicity analysis at the census block group level, we reported results for four largest race-ethnicity groups (total covered in 2010: 113 million census householders, 98.5% of householders with data on income by race-ethnicity): non-Hispanic White (71%), Hispanic (12%), Black (12%), and Asian (3.8%). Thus, for the household income by race-ethnicity analysis (but not for other analyses), Black and Asian categories included both Hispanic and non-Hispanic individuals; for these analyses (but not others), Hispanic Black populations (~0.40% of the population) would be included in results for Hispanic and for Black populations, and Hispanic Asian populations (~0.08%) would be included in results for Hispanic and for Asian populations.

The US Census Bureau defined census blocks as “urban” or “rural”, based on population density and other characteristics (Ratcliffe et al. 2016). We used 2010 census urban/rural block definitions to define a 2010 census block group for all three years: 1990, 2000, and 2010 as rural if all blocks inside it were rural, and we defined the remaining block groups as urban.

Average estimates of ambient air pollution levels for US EPA criteria pollutants were obtained from Center for Air, Climate, and Energy Solutions (CACES) empirical models for the contiguous US (www.caces.us/data). These models incorporate satellite-derived estimates of air pollution, satellite-derived land cover data, land use data, EPA monitoring station data, and universal Kriging (Kim et al. 2020); estimated pollution levels were available by census block at block centroids based on 2010 census boundaries for years from 1990 to 2010 for all pollutants except PM_{2.5} (for which monitoring data and exposure models were only available starting in 1999). Estimated levels of O₃ from the CACES empirical model are 5-month summer averages (specifically, the average during May through September of the daily maximum 8-hour moving average level); for remaining pollutants, estimated levels are annual averages.

CACES model performance during the years studied here (1990, 2000, 2010), as measured by cross-validated R², was 0.84–0.89 for NO₂ and PM_{2.5}, 0.62–0.82 for O₃, 0.56–0.62

for PM₁₀, and 0.32–0.66 for SO₂ and CO (Kim et al. 2020). Mean error across the census years studied was between -0.02 and 0 ppm for CO, -0.04 to 0 ppb for O₃, -0.09 to -0.06 ppb for NO₂, -0.17 to -0.13 ppb for SO₂, -0.31 to -0.26 µg m⁻³ for PM₁₀, and -0.05 to -0.02 µg m⁻³ for PM_{2.5}. Mean bias (MB) was 13% - 22% for SO₂, and <10% for the other pollutants.

Combining Demographic and Air Pollution Data

We matched the CACES empirical model results and the Census demographic data using the 2010 census spatial boundary definitions (from finest to coarsest spatial resolution: block, block group and tract boundaries) for the three census years (1990, 2000, 2010). We matched census block-level CACES model predictions for criteria air pollutants (blocks in 2010 in the contiguous US: $n = \sim 7$ million; ~ 44 residents per block) to census block group-level demographic data (block groups: $n = \sim 22,000$; ~ 1400 residents per block group) by calculating population-weighted mean air pollution levels for all census block centroids in that census block group using census block population data in year 2010. Similarly, to match census tract-level demographic data (tracts: $n = \sim 74,000$; ~ 4200 residents per tract), we calculated the population-weighted mean air pollution levels for all census block groups located within that tract.

Estimating Exposures to Pollutants

We estimated annual pollutant-specific exposures for 1990, 2000, and 2010 based on population-weighted mean predicted ambient air pollution levels for each demographic group (race-ethnicity, income, and income by race-ethnicity). This approach (average ambient air pollution level at residential census block group or tract) is broadly consistent with many examples in research and practice, including EPA monitors, the National Ambient Air Quality Standards, many influential epidemiological studies, and the published empirical models employed here. This article focuses on pollution level disparities rather than health outcomes; in the discussion section we place these findings in context via a brief, simplified calculation of health impacts. We used the finest publicly available census spatial boundary data to estimate exposures for each analysis (income by race-ethnicity: tracts; all other analyses: block groups) based on availability of census demographic data.

The national annual (for O₃, 5-month average; for remaining pollutants, annual-average) exposure for demographic group i (e_i) was calculated for a given pollutant and year as:

$$e_i = \frac{\sum_{j=1}^n c_j p_{ij}}{\sum_{j=1}^n p_{ij}}, \quad [1]$$

where c_j is the predicted average ambient pollution level for block group or tract j , p_{ij} is the population of demographic group i in block group or tract j , and n is the number of block groups or tracts in the analyzed spatial level (contiguous US, 49 “areas” (defined as the District of Columbia plus 48 states), urban vs. rural areas).

National Exposure Disparities Analyses

Our primary metric for quantifying national exposure disparities is the difference in population-weighted average pollution level, as calculated using **Equation (1)**, between the racial-ethnic group with the highest national mean exposure (“most-exposed group”) and the racial-ethnic group with the lowest national mean exposure (“least-exposed group”) among the four racial-ethnic groups (non-Hispanic White, non-Hispanic Black, non-Hispanic Asian, Hispanic); here, the unit of analysis is a racial-ethnic group. This metric has the following advantages: (1) it avoids pre-selecting racial-ethnic groups for comparison and (2) racial-ethnic minority groups

are analyzed separately instead of combined into one group, thereby preserving to some degree the exposure disparities among groups. (We used alternative metrics for analyses by state; see below.) Absolute disparities have closer link with average health, while relative disparities does not depend on exposure scales (Harper et al. 2013). To be more flexible when applying study results on future environmental policy and regulatory, we also reported relative disparities in addition to absolute disparities between two racial-ethnic groups. Relative exposure disparity is calculated as the ratio between the most- and least- exposed racial-ethnic group.

We also investigated exposure disparities based on racial-ethnic minority resident percentages; here, the unit of analysis is bin of census block groups. Each block group bin was defined as single percentile (i.e., 1%) of all block groups stratified by proportion racial-ethnic minority residents. There were approximately 215,000 block groups in 2010, so each block group bin contained approximately 2,150 block groups. To investigate racial-ethnic disparities among block group bins, we rank ordered all census block group bins based on percent of a racial-ethnic minority residents (i.e., people self-reporting any race-ethnicity other than non-Hispanic White). For example, the first block group bin was the first percentile, and consisted of all block groups with between 0% and 0.67% racial-ethnic minority residents; the second block group bin was the second percentile, consisting of all block groups with 0.67% – 0.97% racial-ethnic minority residents; the third block group bin consisted of all block groups with 0.97% – 1.2% racial-ethnic minority residents, and so on through all 100 block group bins. The last block group bin consisted of all block groups with 99% – 100% racial-ethnic minorities. The annual exposure for demographic group i for the p^{th} percentile census block group bin (e_{ip}) was calculated for a given pollutant and year as:

$$e_{ip} = \frac{\sum_{j=1}^{n_p} c_j p_{ij}}{\sum_{j=1}^{n_p} p_{ij}}, \quad [2]$$

where c_j is the average pollution level for block group j , p_{ij} is the population of demographic group i in block group j , and n_p is the number of block groups in the p^{th} percentile block group bin. Absolute disparity is calculated as the exposure difference between block groups with the highest- versus lowest- deciles of proportion racial-ethnic minority residents and relative disparity is calculated as the exposure ratio.

For our national exposure disparities by income analysis, we calculated exposures for the 16 income categories using **Equation (1)**. For our national income by race-ethnicity analysis, we combined estimated air pollution levels with census demographic data including household race-ethnicity and household income data at the census tract level. We then calculated exposures for the four racial-ethnic groups using **Equation (1)** and exposure disparities between most- and least-exposed racial-ethnic group in each income category.

National Analysis of High-End Exposure disparities in 2010

To quantify racial-ethnic disparities at the highest exposure levels, we analyzed the racial-ethnic composition of census block groups above the 90th percentiles of the average pollution level among all census block groups. This was done separately for each pollutant. First, for each of the four largest racial-ethnic groups, we estimated the proportion of that group's national population that lived in a high exposure block group; here, our unit of analysis is a racial-ethnic group. This calculation reflects the proportion of a racial-ethnic group's total US population that lived in heavily polluted (above the 90th percentile) block groups. We performed this calculation for each pollutant and each racial-ethnic group, using **Equation (3)**. The second analysis, which was the converse of the first, investigated the racial-ethnic composition of block groups above the 90th

percentile for average pollution level. Here, our unit of analysis is all block groups above the 90th percentile. This calculation reflects the demographics of only people that lived in heavily polluted block groups. We completed this calculation for each pollutant and each racial-ethnic group using **Equation (4)**.

$$a_i = \frac{\sum_{j=1}^n p_{ij}}{p_{total_national_i}} * 100\%. \quad [3]$$

$$b_i = \frac{\sum_{j=1}^n p_{ij}}{p_{total_block_group}} * 100\%. \quad [4]$$

Here, a_i is the percent of racial-ethnic group i living in a block group with concentration above the 90th percentile for that pollutant, p_{ij} is the population of group i in census block group j , $p_{total_national_i}$ is the total population for group i in the United States, $p_{total_block_group}$ is the total population of census block groups above the 90th percentile in the United States for that pollutant, b_i is (when considering only the people counted towards $P_{total_block_group}$) the percent of people who are in racial-ethnic group i , and n is the number of census block groups above the 90th percentile.

To explore multi-pollutant aspects of high-end exposure, we investigated the proportion of the total US population living in census block groups that were above the 90th percentile for exposure to 0, 1, 2, 3, and 4+ pollutants, for each racial-ethnic group in 2010, using **Equation (3)**.

Sensitivity Analysis on Robustness of National Exposure Disparity Estimates

We conducted three sensitivity tests to investigate the robustness of conclusions based on estimated exposure disparities. First, as a sensitivity test for conclusions based on comparisons of mean values for exposures between groups, we calculated disparities using different metrics of the exposure distribution (10th, 25th, 50th, 75th, 90th percentiles).

The remaining two sensitivity tests investigated whether conclusions here are robust to uncertainty in exposure model predictions. Specifically, in the second sensitivity test, we repeated the analysis of national mean exposures by racial-ethnic group, but for only the population living in a census block group with an EPA monitor in 2010. In this sensitivity test, we used the monitor observations directly as the exposure level, rather than modeling exposures. We then calculated Spearman rank-order correlation of relative disparities by pollutant (between the most- and least- exposed group) between base case and sensitivity test.

In the third sensitivity test, we compared the magnitude of uncertainties in the estimated racial-ethnic exposure disparities with the magnitude of the estimated racial-ethnic exposure disparities. To assess the potential impact of model error on racial-ethnic disparities, we first calculated population-weighted mean error (ME) for each racial-ethnic group, k , using **Equation (5)**:

$$ME_k = \frac{\sum_{i=1}^n (c_{im} - c_{io}) p_{ik}}{\sum_{i=1}^n p_{ik}}, \quad [5]$$

where c_{im} is the modeled average pollution level for block group i , c_{io} is the measured average pollution level across all reporting EPA monitors within census block group i , p_{ik} is the population of demographic group k in block group i , and n is the total number of block groups with EPA monitors. The ME of disparity between two racial-ethnic groups i and j induced by the model was calculated as the difference between population-weighted ME for the two racial-ethnic groups i and j . Calculated uncertainties are based on comparison with EPA measured pollution level in 2010. We then calculated the ratio between the uncertainties in estimated racial-ethnic

exposure disparities (calculated as the difference in population-weighted mean error between the most- and least- exposed racial-ethnic groups) and the estimated racial-ethnic disparities between the most- and least-exposed racial-ethnic groups.

Counterfactual Analysis of Exposure Disparities by Race-ethnicity and Income

We performed a counterfactual analysis to control for differences in income distributions among racial-ethnic groups in estimates of national mean exposures and national average racial-ethnic and income-based exposure disparities. To control for differences in income distributions among racial-ethnic groups, we calculated counterfactual population in each racial-ethnic group using the national income distribution. Then we used a counterfactual population-weighted average to represent shifting the true income distributions of each racial-ethnic group to match the national income distribution. This shifting was performed to control for the effect of income when comparing across racial-ethnic groups. We then calculated population-weighted average exposures for racial-ethnic groups after adjusting (using weighted averages) to match the national income distribution.

The prior paragraph describes comparing racial-ethnic groups after adjusting the income distribution for each racial-ethnic group to match the national income distribution. We also did the converse: comparing income groups after adjusting the racial-ethnic group population distribution for each income group to match the national racial-ethnic group distribution. We then calculated population-weighted average exposure for income categories after adjusting (using weighted averages) to match the national racial-ethnic distribution. We then compared these two counterfactual cases to the true exposure disparity to isolate the effect of differences in income distributions among racial-ethnic groups on our national estimates of exposure disparities by race-ethnicity and income.

Counterfactual Analysis of Migration

We investigated whether changes in racial-ethnic exposure disparities over time were mainly attributable to changes in air pollution levels (“air pollution”) or changes in where people lived (abbreviated as “migration”, but also including immigration and other shifts in demographic patterns). To do so, we employed two counterfactual scenarios (Clark et al. 2017) during two decades (1990 to 2000; 2000 to 2010). For each scenario and year, we calculated exposures for the four largest racial-ethnic groups for the contiguous US population using **Equation (1)** based on census block group data. We then calculated the racial-ethnic exposure disparity between the most- and least-exposed racial-ethnic groups (referred to in this section as “disparity”) for all pollutants with available data (i.e., all except PM_{2.5} in 1990). To analyze 1990 to 2000, we calculated the change in disparity attributable to air pollution changed from 1990 to 2000 levels, with demographics remained constant at 1990 values (counterfactual scenario A), and used 1990 air pollution levels with demographic data changed from 1990 to 2000 values (counterfactual scenario B). To estimate the separate contribution of changes in *air pollution* during 1990 to 2000, we divided the disparity-changes from counterfactual scenario A by the “true” calculated disparity-change between 1990 and 2000 (i.e., using 1990 air pollution levels with 1990 demographic data, and using 2000 air pollution levels with 2000 demographic data). Similarly, to estimate the separate contribution of *migration* during 1990 to 2000, we divided the disparity-changes from counterfactual scenario B by the “true” calculated disparity change between 1990 and 2000. Lastly, we used an analogous approach to analyze the next decade: 2000 to 2010.

Exposure Disparities Comparison Metrics for States

We investigated patterns in absolute exposure disparities among the 48 states of the contiguous US plus District of Columbia (hereafter, “49 areas”) using two metrics for racial-ethnic exposure disparity. First, we used **Equation (6)** to calculate an area-specific population-weighted disparity for each of the four racial-ethnic groups and the area average relative to the pollutant’s national mean. Second, for each area, we used **Equation (7)** to calculate a normalized population-weighted disparity between two groups: all racial-ethnic minorities combined, and non-Hispanic Whites (Fig. 4, right column). This metric has the advantage of consistently comparing, for each area, exposures between racial-ethnic minorities and the majority racial-ethnic group (non-Hispanic Whites, 64% of the population). Lastly, we averaged both metrics across the six pollutants.

$$d1_r = \frac{e_r - e_{area}}{e_{national}} \quad [6]$$

$$d2_r = \frac{e_{minority} - e_{NH-White}}{e_{national}} \quad [7]$$

For each area and pollutant, $d1_r$ is the normalized population-weighted disparity for racial-ethnic group r , e_r is the average exposure for racial-ethnic group r in the area, e_{area} is the average exposure for all people in the area, $e_{national}$ is the average exposure for all people in the United States, $e_{minority}$ is the average exposure for all racial-ethnic minorities in the area, and $e_{NH-White}$ is the average exposure for all non-Hispanic Whites in the area.

Results

National Exposure Disparities by Race-Ethnicity and Income in 2010

By Race-Ethnicity

To investigate national disparities in exposure to criteria air pollution by race-ethnicity, we first compared national population-weighted mean exposures by US census self-reported race-ethnicity in 2010, the most recent decennial census year with available data. We first present results for differences among subpopulations (unit of analysis: racial-ethnic group), then we present differences among locations, depending on the proportion of each racial-ethnic group residents in that location (unit of analysis: census block groups binned by proportion of racial-ethnic minority residents).

Estimated national mean air pollution exposures were higher for all three racial-ethnic minority groups than for non-Hispanic Whites for four of the six criteria pollutants (CO, NO₂, PM_{2.5}, and PM₁₀) (**Table 1 and Fig. 1**). Disparities between the most- and least-exposed racial-ethnic groups were largest for NO₂ (absolute disparity: 4.6 ppb, relative disparity: 1.6); intermediate for SO₂ (0.29 ppb, 1.2), PM₁₀ (3.0 µg m⁻³, 1.2), CO (0.044 ppm, 1.1), and PM_{2.5} (1.2 µg m⁻³, 1.1); and lowest for O₃ (1.6 ppb, 1.0). For all six pollutants, the most-exposed group was a racial-ethnic minority group: for PM_{2.5} and SO₂, national mean exposures were highest for the non-Hispanic Black population; for CO, NO₂, and O₃, the non-Hispanic Asian population; and for PM₁₀, the Hispanic population. For CO, NO₂, PM_{2.5}, and PM₁₀, national mean exposures were lowest for non-Hispanic White population; for O₃, Hispanic population; and for SO₂, non-Hispanic Asian population.

Sensitivity test on robustness of conclusions based on mean values showed that, for all pollutants, the rank-order (i.e., most- to least-exposed racial-ethnic group, among the four racial-ethnic groups) was consistent throughout the exposure distributions (**Fig. 1**). The remaining two sensitivity tests investigated whether conclusions here are robust to uncertainty in exposure

model predictions. Results reveal that the conclusions are robust to exposure model uncertainty. Results for analyzing only the population living in a census block group with an EPA monitor in 2010 were essentially the same as results using exposure model predictions: the non-Hispanic Whites group was the least-exposed group on average for most pollutants (CO, NO₂, PM_{2.5}, PM₁₀, and O₃) and the relative disparities by pollutant (between the most- and least- exposed group on average) were highly-correlated (Spearman rank-order correlation between base case and sensitivity test: 0.89). The ratio between the uncertainties in estimated racial-ethnic exposure disparities and the estimated racial-ethnic disparities between the most- and least-exposed racial-ethnic groups were small: on average, 0.7% (if using absolute values of the ratio, 8%). The largest absolute ratio was -17% [O₃]. That result indicated that the uncertainty in the exposure model predictions was always small compared to the predicted racial-ethnic exposure disparities.

We also performed a complementary analysis to determine whether average air pollution levels varied based on the racial-ethnic composition of a given census block group. For CO, NO₂, PM_{2.5}, and PM₁₀, average pollution levels were higher in census block groups with higher proportions of racial-ethnic minority residents (**Fig. 2**). For O₃, estimated average levels were approximately equal across census block group bins, regardless of census block group racial-ethnic characteristics (**Fig. 2**). For SO₂, estimated average levels were generally higher in census block group bins with the highest and lowest proportions of racial-ethnic minority residents (i.e., higher in more racially segregated census block groups) (**Fig. 2**). This approach also reveals that the disparities were much larger for NO₂ than for other pollutants. The disparity in average air pollution levels between block groups with the highest- versus lowest- deciles of proportion racial-ethnic minority residents (block groups with >88% vs. <4% racial-ethnic minority residents) was larger for NO₂ (absolute disparity: 9.4 ppb, relative disparity: 3.1) than for other pollutants (relative disparity range: 0.8 – 1.4, median: 1.1)

Lastly, we investigated racial-ethnic disparities in exposure to the highest air pollution levels. First, for each racial-ethnic group we calculated the proportion of people nationally who lived in a block group with air pollution levels above the 90th percentile for each pollutant. Averaged across all pollutants, the proportion of people nationally who lived in those highest-exposure block groups was: 9.6% for the overall population, 17% for the Hispanic population, 15% for the non-Hispanic Asian population, 12% for the non-Hispanic Black population, and 7.2% for the non-Hispanic White population. Next, we calculated the racial-ethnic composition of the block groups with air pollution levels above the 90th percentile for each pollutant. Racial-ethnic minorities were more likely than non-Hispanic Whites to live in a census block group with air pollution levels above the 90th percentile for all pollutants (range: 1.1× to 4.1×, median: 2.1×) except SO₂ (0.88×). Racial-ethnic minorities were also disproportionately likely to live in a census block group having *multiple* pollutants with levels above the 90th percentile. For example, the proportion of population living in a census block group with levels above the 90th percentile for four or more criteria pollutants was 5.2% for Hispanic population (3.6× the national population average proportion), 2.2% for non-Hispanic Asian population (1.5× the average), 1.9% for non-Hispanic Black population (1.3× the average), and 0.36% for non-Hispanic White population (0.25× the average) (for comparison: 1.4% for the overall US population).

By Income

To investigate national exposure disparities by income, we first compared national mean exposures to criteria air pollution by census income category in 2010. For all pollutants except O₃, national mean exposures were higher for lower-income than for higher-income households

(**Fig. 3**). Comparing national mean exposures for lowest-income (<\$10,000; 7.2% of the households with income data) versus for highest-income (>\$200,000; 4.2%) households, exposures for lowest income households were 16% higher for SO₂, 6.6% higher for PM_{2.5}, and 5.2% higher for PM₁₀. For NO₂, CO, and O₃, exposures for lowest- and highest-income households were similar (~±2%). Based on differences in average exposures between the approximate 25th and 75th percentiles for income (\$20,000-25,000 [midpoint: \$22,500], \$75,000-100,000 [midpoint: \$87,500]), a \$10,000 increase in income was associated with an average reduction in concentration (expressed as a percent of the national mean concentration) of 0.90% for SO₂, 0.41% for PM_{2.5}, 0.36% for NO₂, and 0.22% for PM₁₀ and CO, and an increase of 0.16% for O₃.

By Both Race-Ethnicity and Income

In this section, we present exposure disparities accounting for both race-ethnicity and income together for census householders (hereafter, “households”). (Reflecting publicly available census data for racial-ethnic groups by income category, for this section only, the Black and Asian groups include Hispanic and non-Hispanic individuals.)

For all six pollutants, the absolute exposure disparity between the most- and least-exposed racial-ethnic groups was much larger (on average, ~6× larger) than the absolute exposure disparity between the lowest- and highest-income categories in 2010 (relative disparity ~ 1.2× larger). For all income levels and pollutants, the most-exposed racial-ethnic group was a racial-ethnic minority group (**Fig. 3**). For five of the six pollutants (not SO₂; **Fig. 3**), average exposures were higher on average for Black households at the approximate 75th percentile for income (income category midpoint: \$87,500) than for non-Hispanic White households at the approximate 25th percentile for income (midpoint: \$22,500). Racial-ethnic exposure disparities tended to be comparatively smaller at higher incomes than at lower incomes (except for O₃), but the size of that effect was modest. For example, the exposure absolute disparity between the most- and least-exposed racial-ethnic groups (**Fig. 3**) was, on average, 9.5% lower for households at the approximate 75th percentile than at the approximate 25th percentile of income.

Income distributions varied by racial-ethnic group. For example, non-Hispanic White households represented 61% of the lowest income category (<\$10,000) and 85% of the highest income category (>\$200,000), versus 23% and 3.5%, respectively, for non-Hispanic Black households, 13% and 4.3% for Hispanic households, and 3.5% and 6.9% for non-Hispanic Asian households. To quantify racial-ethnic exposure disparities after accounting for racial-ethnic income distribution variation, we calculated the racial-ethnic exposure disparity within each income category in 2010 and averages across all 16 income categories. The resulting national absolute exposure disparity between most- and least-exposed racial-ethnic groups normalized to national mean exposure (i.e., expressed as a percent of the national mean concentration) was 58% for NO₂, 4.5% for O₃, 12% to 17% for the remaining pollutants. Conversely, to quantify income exposure disparities after accounting for race-ethnicity, we calculated the absolute income disparity within each racial-ethnic group and averaged across the four racial-ethnic groups. The resulting national absolute exposure disparity between lowest and highest income categories normalized to national mean exposure was 15% for SO₂, -2.9% for O₃, 2.7% to 6.3% for the remaining pollutants.

We also conducted two counterfactual analyses of exposure disparities by race-ethnicity and income to quantify the contribution of national racial-ethnic disparities in income in explaining national racial-ethnic disparities in air pollution exposure. Both counterfactuals

slightly shifted the calculated exposure disparities, but support the conclusion that racial-ethnic exposure disparities were distinct from, and larger than, exposure disparities by income. The first counterfactual shifted the absolute disparity between most- and least-exposed racial-ethnic group normalized to pollutant's national mean exposure by 0.03 percentage units on average (average of absolute values: 1.0 percentage units; range among pollutants: -1.9 to +2.4 percentage units). The second counterfactual shifted the absolute disparity between highest and lowest income categories normalized to pollutant's national mean exposure by 1.1 percentage units (average of absolute values: 1.5 percentage units; range among pollutants: -1.3 to +4.4 percentage units).

Racial-ethnic Exposure Disparities by State and by Urbanicity in 2010

By State

We explored how exposures varied by state, pollutant, and racial-ethnic group in 2010 (**Fig. 4**). The analysis separately considers the District of Columbia plus the 48 states of the contiguous US (hereafter, "49 areas"). There are 294 pollutant-area combinations (6 pollutants $\times$ 49 areas) and 1176 pollutant-area-groups (294 pollutant-areas $\times$ 4 racial-ethnic groups). For this section, we define $\pm 5\%$ (all percentages used in this section were expressed as a percent of the national mean concentration) as "similar to", and therefore report examples where exposures differ from the average by $>5\%$ (or, in a sensitivity test, $>20\%$). For example, " $>5\%$ lower-than-average" means the exposure is lower-than-average by an amount greater than 5%.

Overall, several spatial patterns emerge across areas. First, racial-ethnic exposure disparities were ubiquitous among US areas. In all 49 areas, one or more racial-ethnic groups experienced exposures $>5\%$ of the area average exposure in 2010. Second, racial-ethnic minority populations within areas were much more likely to have been more-exposed versus less-exposed than average; in contrast, non-Hispanic White populations within areas experienced exposures $>5\%$ above average in no areas. Third, having exposures $>5\%$ lower-than-average within an area was much more likely to happen for non-Hispanic White populations than for racial-ethnic minority populations (**Fig. 4**, right column). Fourth, racial-ethnic exposure disparities were, on average, largest for NO_2 and smallest for O_3 among areas.

Those findings reflect underlying trends across areas, pollutants, and racial-ethnic groups. For example, for the non-Hispanic White group, 87% of the 294 pollutant-areas had exposures that were similar ($\pm 5\%$) to the average, 13% had exposures $>5\%$ less than average, and none were $>5\%$ greater than average. In contrast, for exposures for the three racial-ethnic minority groups, 42% (of 882 pollutant-area-groups) were $>5\%$ greater than average, 55% were $\pm 5\%$ of the average, and only 4% were $>5\%$ less than average. Thus, within individual areas, the non-Hispanic White group was exposed to pollution levels that were similar to or cleaner than average, whereas the three racial-ethnic minority groups were more likely to be exposed to dirtier rather than cleaner pollution levels. For example, averaged across pollutants, the proportion of the 49 areas for which exposures were $>5\%$ greater than average is 73% for non-Hispanic Blacks, 57% for Hispanics, 35% for non-Hispanic Asians, and zero for non-Hispanic Whites.

The three racial-ethnic minority groups were disproportionately *likely* to be the *most*-exposed group, and disproportionately *unlikely* to be the *least*-exposed group of the four racial-ethnic groups across the 49 areas. For example, the most-exposed group (for all cases, not just cases $>5\%$ greater than average) was the non-Hispanic Black group for 45% of the 294 pollutant-areas, the Hispanic group for 29%, the non-Hispanic Asian group for 18%, and non-Hispanic

White group for 7.5%. In contrast, the least-exposed group was rarely a racial-ethnic minority group (~8% of all 294 pollutant-areas for the non-Hispanic Black and for Hispanic group, 15% for the non-Hispanic Asian group) and was usually (70% of pollutant-areas) the non-Hispanic White group.

As a sensitivity test, we changed the analysis threshold to exposures >20% greater than average (rather than 5%). Here, we again found that the air pollution disproportionately impacted racial-ethnic minority groups. For example, exposure disparities >20% of national mean exposure for one or more pollutant-groups occurred for 67% of areas (**Fig. 4**, left four columns for six pollutants), further emphasizing that disparities were widespread across areas in 2010.

Fig. 4 reveals differences among states. For example, the four most populous states (California, Florida, New York, Texas), all have large, racially/ethnically diverse urban areas. However, average disparities between racial-ethnic minority populations and non-Hispanic White populations (**Fig. 4** bottom right) were notably larger (on average, 6× larger) for California and New York than for Florida and Texas. Some small, relatively rural states also had substantial exposure disparities. Examples include NO₂ in Nebraska (19%) and PM_{2.5} in Nebraska (8.1%).

By Urbanicity

We investigated racial-ethnic and income-based exposure disparities in 2010 separately for block groups that were defined as urban (89% of the population) versus rural (11% of the population).

The racial-ethnic exposure disparities were generally larger for urban than for rural block groups. Specifically, the average exposure disparity between the most- and least-exposed racial-ethnic group was 5.5× larger for absolute disparity (1.2× for relative disparity) for urban block groups than for rural block groups for NO₂, 3.1× (1.0×) larger for O₃, 2.4× (1.1×) larger for CO, 1.8× (1.0×) larger for SO₂, and 1.2× (1.0×) larger for PM₁₀. In contrast, for PM_{2.5}, the average racial-ethnic exposure disparity was 1.2× (1.0×) larger for rural block groups than for urban block groups.

The most- and least-exposed racial-ethnic groups (of the four largest groups) differed between urban and rural areas for SO₂ and for O₃. For SO₂, the most-exposed racial-ethnic group was the non-Hispanic Black group in urban areas and the non-Hispanic White group in rural areas. For O₃, the most-exposed racial-ethnic group was the non-Hispanic Asian group in urban areas and non-Hispanic White group in rural areas. For the remaining four pollutants, the most-exposed group was a racial-ethnic minority group in urban and in rural areas.

Exposure disparities by income category were also larger in urban than in rural areas. Absolute exposure disparities between lowest and highest income category were 1.1× [PM_{2.5}] - 25× [O₃] (median: 3.5×) greater (0.98× to 1.1× for relative disparity, median: 1.0×) in urban than in rural areas. Of the 12 pollutant-urbanicity categories (6 pollutants × 2 urbanities), exposures were higher for the lowest-income category than for the highest-income category in all cases except for O₃ in urban areas and for NO₂ in rural areas.

Changes in National Exposures and Exposure Disparities from 1990 – 2010

Criteria air pollution levels have declined in the United States in the decades following the 1990 Clean Air Act amendments (US EPA 2020). To investigate if these reductions have led to reductions in racial-ethnic exposure disparities, we compared average exposures by racial-

ethnic group from 1990 to 2010, for five of the pollutants. Exposure model results for PM_{2.5} were only available from 2000 to 2010, so those results are presented separately.

National mean pollution levels of all six pollutants fell over the study period. For example, from 1990 to 2010, the national mean exposures decreased for all five pollutants by an average of 40% (range: -6% [O₃] to -71% [SO₂]; -34% to -55% for remaining three pollutants). PM_{2.5} exposures decreased 29% from 2000 to 2010.

The average exposure disparities also declined from 1990 – 2010. The amount of change depends in part on whether one considers *absolute* or *relative* disparities. In terms of *absolute* disparities, the disparities between the most- and least-exposed racial-ethnic groups decreased on average by 69% across the five pollutants. The largest change was an 88% decrease for CO disparities (0.40 ppm in 1990, 0.044 ppm in 2010, a 0.35 ppm [i.e., 88%] change) and the smallest change was a 54% decrease for NO₂ (9.8 ppb [1990], 4.6 ppb [2010], a 5.3 ppb change). From 2000 to 2010, PM_{2.5} disparities decreased by 35% (1.9 µg m⁻³ [2000], 1.2 µg m⁻³ [2010], a 0.66 µg m⁻³ change).

In terms of *relative* disparities, the disparities between the most- and least-exposed racial-ethnic groups decreased on average by 14 percentage units. The greatest change was decrease for CO (disparities: 1.7 [1990], 1.1 [2010]) and the smallest was decrease for O₃ (1.1 [1990], 1.04 [2010]); remaining pollutants were between 0.070 – 0.074 decrease in relative disparity. PM_{2.5} relative disparity remained constant (~1.1) from 2000 to 2010.

Shifting the comparison to the proportion of each racial-ethnic group in a location (unit of analysis: census block group) yields similar conclusions for changes in disparities during 1990 to 2010. For example, absolute air pollution level disparities between census block group bins with the highest versus lowest deciles of proportions of racial-ethnic minority residents (90th - 100th versus 1st - 10th percentiles in **Fig. 2**) decreased for four pollutants, on average by 60% of the national mean exposures (CO, NO₂, PM₁₀, SO₂). For O₃, disparities decreased slightly, from near-zero in 1990 to 0.46 ppb (which is 1.0% of the national mean exposure) in 2010. PM_{2.5} disparities decreased 58% from 2000 to 2010.

In addition to national changes, we investigated changes in absolute racial-ethnic exposure disparities from 1990 to 2010 by state and by urban versus rural area. Most states (>75%) experienced a reduction in racial-ethnic exposure disparities for pollutants except for PM₁₀ (and, except for PM_{2.5} during 2000-2010). Urban areas experienced larger reductions in racial-ethnic exposure disparities than did rural areas for NO₂ and PM₁₀ (13× larger reductions in urban areas, for both pollutants), CO (2.4×), and SO₂ (1.2×). Conversely, PM_{2.5} (during 2000-2010) and O₃ (during 1990-2010) had larger racial-ethnic disparity reductions for rural than for urban (2.4× and 3.4× larger in rural areas, respectively).

Finally, we investigated whether the changes in absolute racial-ethnic exposure disparities from 1990 to 2010 were more attributable to changes in air pollution levels or to changes in demographic patterns (migration, immigration, and other factors). Based on a counterfactual analysis, reductions in racial-ethnic exposure disparities between the most- and least- exposed racial-ethnic groups were mainly attributable to changes in air pollution levels rather than to changes in demographic patterns. On average across all pollutants, 87% of disparities decrease were attributable to changes in air pollution levels from 1990 to 2000 (excluded PM_{2.5}), and 97% from 2000 to 2010.

Discussion

Our findings indicated that in 2010, on average, racial-ethnic minority populations were exposed to higher average levels of transportation-related air pollution (CO, NO₂) and particulate matter (PM_{2.5}, PM₁₀) than non-Hispanic White populations, even after accounting for uncertainties in the predictions from exposure models. This finding is consistent with prior national studies of NO₂, PM_{2.5}, and PM₁₀ (Clark et al. 2017; Kravitz-Wirtz et al. 2016; Mikati et al. 2018; Tessum et al. 2019). Our findings on “which group was most-exposed?” varied by pollutant, but in all six cases the most exposed group was a racial-ethnic minority group. That result is consistent with prior national studies, which have reported, for example, highest NO₂ exposures for Hispanic Black and non-Hispanic Asian populations (Clark et al. 2017), and highest proximities to industrial PM_{2.5} emissions (Mikati et al. 2018) and highest exposures to industrial air toxins for non-Hispanic Black populations (Ard 2015). We found that racial-ethnic minorities were 2.2× more likely to live in a census block group with highest air pollution levels (above 90th percentile). Those results are consistent with existing literature on disproportionate risks for racial-ethnic minorities (Collins 2016) and on groups or locations with higher risks for one environmental factor having higher risks for other factors too (Morello-Frosch and Lopez 2006; Su et al. 2012).

We found that air pollution exposures were generally higher for lower-income households (for all pollutants except O₃). This finding is consistent with previous national research (e.g., for industrial PM_{2.5} emissions (Mikati et al. 2018), industrial air toxins (Ard 2015), and PM_{2.5} and NO₂ (Clark et al. 2014; Kravitz-Wirtz et al. 2016)). Additionally, we found that absolute racial-ethnic exposure disparities were distinct from, and were much larger (~6×) than, exposure disparities by income. The findings are *inconsistent* with the idea that racial-ethnic exposure disparities can be explained by, or are “merely” a reflection of, income disparities among racial-ethnic groups.

State-level results may be especially useful given the important role that states play in air pollution and environmental policy making (Abel et al. 2015). Exposures >5% greater than national mean exposure within states were common (42%) for racial-ethnic minority populations, but not for non-Hispanic white populations. Exposure disparities varied substantially among states, even among states with similar characteristics (e.g. large urban areas, population, region). Our results emphasize differences among states in the level and makeup of exposure disparities, yet also demonstrate that exposure disparities were ubiquitous, including both large and small states, and states in all regions of the US, in 2010.

Our analyses by urbanicity were in part motivated by, and reflect, urban-rural differences in demographics and air pollution levels (Clark et al. 2017; Mikati et al. 2018; Rosofsky et al. 2018). Racial-ethnic disparities were larger for urban block groups for all pollutants except PM_{2.5}. NO₂ has largest ratio between urban and rural racial-ethnic absolute disparity (5.5× larger). The NO₂ results are consistent with prior research (Clark et al. 2017). PM_{2.5} and O₃ had larger absolute racial-ethnic disparity reductions for rural than for urban areas, likely reflects the fact that O₃ and most of PM_{2.5} are secondary pollutants versus the others being mainly primary pollutants. Controlling for urbanicity, exposures were mostly higher for the lowest income category than the highest. Absolute income disparities were also larger by an average of 7.5 times in urban than in rural areas.

Regulations such as 1990 Clean Air Act Amendments have achieved substantial reductions in the concentrations of many pollutants. Our analysis reveals that, as a co-benefit, falling pollution levels have reduced absolute exposure disparities among racial-ethnic groups. These findings are consistent with previous national research for NO₂, PM_{2.5}, and industrial air

toxins (Ard 2015; Clark et al. 2017; Kravitz-Wirtz et al. 2016; Colmer et al. 2020). We found that a larger share of the racial-ethnic exposure disparity reduction was attributable to air pollution level reduction rather than changes in demographic and residential patterns.

Exposure disparities link with health disparities. Based on the magnitude of exposure disparities (e.g., 2010 national-average PM_{2.5} exposures for non-Hispanic Black people are 1.0 µg m⁻³ higher-than-average), the resulting health disparities are likely to be substantial (thousands of additional premature mortalities per year); future research could usefully extend our exposure disparity results to provide rigorous, comprehensive investigation of the associated health impacts. Our results reflect that exposure disparities have different patterns at different spatial levels (urban/rural, state); future research could explore these aspects further, for example a spatial decomposition of national exposure disparities.

Our study has several limitations. The finest spatial scale of publicly-available Census demographic data for race-ethnicity and income is at Census block groups level; we were not able to assess exposures at finer spatial scales. Our exposure disparity calculation approach does not account for (1) daily mobility for work, shopping, recreation, and other activities, (2) direct indoor exposure to indoor sources such as cigarette smoke, cooking emissions, or incense, (3) indoor-outdoor relationships in pollution levels, such as particle losses during airflow in ducts or ozone losses to indoor surfaces, or (4) occupational exposures. Our exposure disparity estimates were limited by uncertainties in the CACES exposure model predictions and Census demographic data. Due to limitations in availability of national criteria air pollution concentration observations, our uncertainty analysis was limited to US EPA monitoring locations; we were not able to test potential exposure errors at locations without monitors on the national scale. Additionally, one important dimension not considered here is responsibility for generating pollution. Recent analysis suggests that Hispanic and Black populations have disproportionately lower contributions to the emissions that contribute to PM_{2.5} air pollution (Tessum et al. 2019).

Our study provides the first national analysis of air pollution exposure disparities among income and racial-ethnic groups, for all criteria pollutants (except lead), including trends across time (by decade, 1990–2010) and spatial location (by state and for urban vs rural areas). On average, exposures were generally higher for racial-ethnic minority populations than for non-Hispanic White populations. Exposures were also higher for the lowest-income households than for the highest-income households. However, exposure disparities by race-ethnicity were not explained by disparities in income. Racial-ethnic exposure disparities declined from 1990 to 2010, but still existed in all states in 2010. Among pollutants, national racial-ethnic exposure disparities were largest for NO₂ and smallest for O₃.

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Tables

Table 1. Population distribution and population-weighted exposure distribution for six criteria pollutants for four main racial-ethnic groups in year 2010.

Demographic	Non-Hispanic White	Non-Hispanic Black	Hispanic	Non-Hispanic Asian	Entire Population
Proportion of population	64%	12%	16%	4.6%	100%
PM_{2.5} (µg m⁻³)					
10 th percentile	6.1	7.9	6.5	6.7	6.3
25 th percentile	7.7	9.2	7.7	8.2	7.9
50 th percentile	9.3	10	9.6	9.7	9.5
Mean (SD)	9.1 (2.2)	10 (1.8)	9.4 (2.2)	9.4 (1.9)	9.3 (2.2)
75 th percentile	11	11	11	11	11
90 th percentile	12	13	12	12	12
NO₂ (ppb)					
10 th percentile	3.1	3.8	4.6	5.4	3.4
25 th percentile	4.3	5.8	6.6	7.5	4.9
50 th percentile	6.2	8.7	9.5	10	7.4
Mean (SD)	7.2 (4.1)	9.7 (5.3)	11 (6.1)	12 (5.9)	8.7 (5.1)
75 th percentile	8.9	12	15	15	11
90 th percentile	12.5	18	21	21	16
O₃ (ppb)					
10 th percentile	38	39	33	39	38
25 th percentile	43	43	42	44	43
50 th percentile	47	47	46	47	47
Mean (SD)	46 (6.0)	46 (6.1)	45 (7.2)	46 (5.9)	46 (6.2)
75 th percentile	50	50	49	50	50
90 th percentile	52	53	52	53	52
SO₂ (ppb)					
10 th percentile	0.91	1.0	0.83	0.79	0.95
25 th percentile	1.1	1.2	1.0	1.0	1.2
50 th percentile	1.5	1.6	1.3	1.2	1.5
Mean (SD)	1.6 (0.65)	1.7 (0.63)	1.4 (0.55)	1.4 (0.58)	1.6 (0.64)
75 th percentile	1.9	2.1	1.7	1.7	2.0
90 th percentile	2.4	2.5	2.2	2.3	2.5
PM₁₀ (µg m⁻³)					
10 th percentile	12	14	15	14	13
25 th percentile	14	16	17	16	15
50 th percentile	17	19	20	19	18
Mean (SD)	18 (4.4)	19 (3.7)	21 (4.9)	20 (4.5)	18 (4.6)
75 th percentile	21	21	23	22	22
90 th percentile	23	23	28	25	24
CO (ppm)					
10 th percentile	0.23	0.25	0.26	0.27	0.24

25 th percentile	0.27	0.29	0.30	0.30	0.28
50 th percentile	0.31	0.32	0.34	0.34	0.31
Mean (SD)	0.30 (0.057)	0.32 (0.067)	0.35 (0.079)	0.35 (0.071)	0.31 (0.066)
75 th percentile	0.33	0.35	0.39	0.38	0.35
90 th percentile	0.37	0.40	0.45	0.45	0.39

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Fig. 1. Distribution of exposure to pollutants in years 1990, 2000, and 2010, stratified by racial-ethnic group, for (A) PM_{2.5}, (B) NO₂, (C) O₃, (D) SO₂, (E) PM₁₀, and (F) CO. For all panels, the lowest bound represents the 10th percentile value, the box ranges from the 25th to 75th percentile, the horizontal line in the box represents the median, and the highest bound represents the 90th percentile value. Color circles indicate the national population-weighted mean. PM_{2.5} has no estimates for 1990 because of a lack of monitoring data prior to 1999. “NH” refers to non-Hispanic. “Hispanic” refers to Hispanic of any race(s).

Fig. 2. Relationship between the proportion of racial-ethnic minority residents in census block groups and average criteria air pollution concentrations in the years 1990, 2000, and 2010 for A) PM_{2.5}, (B) NO₂, (C) O₃, (D) SO₂, (E) PM₁₀, and (F) CO. For each panel, the bold portion of the line indicates the 25th to 75th percentile of census block groups, the thin line indicates the 10th to 90th percentile, the dashed line indicates the 1st to 99th percentile, and the diamond icon indicates the 50th percentile.

Fig. 3. Population-weighted criteria air pollution concentration in 2010 for 16 household income groups, stratified by race-ethnicity, for (A) PM_{2.5}, (B) NO₂, (C) O₃, (D) SO₂, (E) PM₁₀, and (F) CO. For all panels, each data point represents pollution exposure for one income category and racial-ethnic group. “NH White” refers to non-Hispanic White. “Hispanic” refers to Hispanic of any race(s). “Asian” refers to Hispanic and non-Hispanic Asian. “Black” refers to Hispanic and non-Hispanic Black. Values plotted for household income are, for values below \$200k (i.e., for the first 15 income categories), the midpoint value; for the highest income category (“>\$200k”), the value plotted is the low end of the range (\$200k).

average across the six pollutants. Columns 1-4: exposure disparity relative to state average; calculated as mean exposure for a racial-ethnic group in that state minus the overall mean for that state, then divided by the national overall mean. Column 5: exposure disparity for racial-ethnic minorities relative to the majority group; calculated as mean exposure for racial-ethnic minorities minus mean exposure for non-Hispanic Whites, then divided by the national overall mean. Mean values are population-weighted. States displayed in white indicate that the disparity is within $\pm 5\%$ of the national overall mean. Purple shading indicates that mean exposures are higher-than-average by more than 5% of the national overall mean (columns 1-4) or that mean exposures are higher for racial-ethnic minorities than for the majority, by more than 5% of the national overall mean (column 5). Orange shading indicates the reverse: mean exposures are higher-than-average for that group (columns 1-4) or mean exposures are higher for racial-ethnic minorities than for non-Hispanic Whites (column 5), and the disparity is greater than 5% of the national overall mean. “NH” refers to non-Hispanic. “Hispanic” refers to Hispanic of any race(s).

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