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March 1, 2021

Via Electronic Delivery[1]

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RE: Petition for Reconsideration of "Review of the Ozone National Ambient Air Quality Standards," 85 Fed. Reg. 87,256 (Dec. 31, 2020).

Dear Acting Administrator Nishida and Ms. Murphy:

Please find attached a Petition for Reconsideration submitted on behalf of the States of New York, California, Connecticut, Illinois, Maryland, Minnesota, New Jersey, Oregon, Rhode Island, Vermont, Washington, and Wisconsin; the Commonwealths of Massachusetts,

[1] This Petition is submitted electronically in light of the COVID-19 pandemic and EPA's guidance with respect to hard copy submissions while Agency staff is teleworking. *Notice Regarding "Hard Copy" Submissions to EPA During the COVID-19 National Emergency* (May 12, 2020), https://www.epa.gov/aboutepa/notice-regarding-hard-copy-submissions-epa-during-covid-19-national-emergency.

Pennsylvania, and Virginia; the District of Columbia; and the City of New York, with respect to the above referenced action, Docket ID EPA–HQ–OAR–2018–0279.

Sincerely,

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(Attachments)

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BEFORE THE HONORABLE JANE NISHIDA, ACTING ADMINISTRATOR UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

IN RE PETITION FOR RECONSIDERATION OF REVIEW OF THE NATIONAL AMBIENT AIR QUALITY STANDARDS FOR OZONE, 85 FED. REG. 87,256 (Dec. 31, 2020)

Submitted by:

The States of New York, California, Connecticut, Illinois, Maryland, Minnesota, New Jersey, Oregon, Rhode Island, Vermont, Washington, and Wisconsin; the Commonwealths of Massachusetts, Pennsylvania, and Virginia; the District of Columbia; and the City of New York

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INTRODUCTION

Pursuant to Clean Air Act Section 307(d), and for the reasons set forth below, the States of New York, California, Connecticut, Illinois, Maryland, Minnesota, New Jersey, Oregon, Rhode Island, Vermont, Washington, and Wisconsin; the Commonwealths of Massachusetts, Pennsylvania, and Virginia; the District of Columbia; and the City of New York (collectively, "State Petitioners") hereby petition the U.S. Environmental Protection Agency (EPA) for reconsideration of its final action not to strengthen the primary and secondary National Ambient Air Quality Standards (NAAQS) for ozone. This final action, titled "Review of the Ozone National Ambient Air Quality Standards," is published in the Federal Register at 85 Fed. Reg. 87,256 (Dec. 31, 2020) ("Final Rule"). In the Final Rule, EPA decided that: (1) the current primary standard should be retained without revision because it is sufficient to protect public health with an adequate margin of safety; and (2) the current secondary standard should be retained without revision because it is sufficient to protect the public welfare. EPA's decision not to strengthen the ozone NAAQS fails to protect the public health and welfare from harm as required under the Clean Air Act. Accordingly, State Petitioners filed a petition for review of EPA's Final Rule on January 19, 2021,[1] seeking a determination that this final action is unlawful, arbitrary and capricious, and therefore must be vacated.

Reconsideration of the Final Rule is also warranted. As discussed below, State Petitioners have raised objections that arose after the end of the comment period and that concern issues of central relevance to the adoption of the Final Rule. 42 U.S.C. § 7607(d)(7)(B). In addition, State

[1] *State of New York, et al. v. EPA, et al*., Case No. 21-1028 (D.C. Cir.).

Petitioners request that EPA grant discretionary reconsideration of the Final Rule to engage in a reasoned review of all of the evidence now before the agency.

First, EPA must grant reconsideration in light of new evidence from a recent study on the association between long-term exposure to ozone pollution and hospital admissions among Medicare participants.[2] *See* Attachment A. The study demonstrates that ozone poses significant risks to the cardiovascular and respiratory health of elderly people within the United States—a population that is already considered at-risk.[3] Because the grounds for these objections arose after the close of the public comment period and are of central relevance to EPA's decision to retain the existing standards for ozone, EPA must reopen public comment and reconsider the Final Rule. 42 U.S.C. § 7607(d)(7)(B). EPA must impart all of the procedural rights that "would have been afforded had the information been available at the time the rule was proposed." *Id.*

Second, EPA should grant reconsideration to conduct a complete and meaningful review of information in certain epidemiologic studies about respiratory effects, cardiovascular effects, and mortality associated with ozone exposure. After the close of public comments, EPA "provisionally considered" an unspecified number of the many studies cited by State Petitioners in their comment letter dated October 1, 2020. *See* 85 Fed. Reg. at 87,262. Based on this cursory, "provisional consideration," EPA determined that information contained in the studies did not warrant reopening the review of the air quality criteria to enable EPA, the Clean Air Scientific Advisory Committee (CASAC), and the public to consider the studies further. *Id*.

[2] Yazdi, Mahdieh D., et al. *Long-Term Association of Air Pollution and Hospital Admissions Among Medicare Participants Using a Doubly Robust Additive Model, Circulation.* 2021;143:00–00. DOI: 10.1161/CIRCULATIONAHA.120.050252.

[3] *Id*.

EPA's determination—first announced in the Final Rule—ignored important new evidence demonstrating a need for more stringent ozone standards to protect public health and welfare.

Third, EPA should grant reconsideration to consider recommendations from the Government Accountability Office (GAO) in its recent report titled, *AIR POLLUTION Opportunities to Better Sustain and Modernize the National Air Quality Monitoring System* (November 2020).[4] *See* Attachment B. The report, which potentially casts doubt on the sufficiency of state ozone data used by EPA in its exposure and risk analysis, further calls into question EPA's decision that the existing primary standard of 70 ppb protects public health with an adequate margin of safety.

STANDARD FOR RECONSIDERATION

EPA must convene a reconsideration proceeding if a person raising an objection shows: (1) it was "impracticable" to raise the objection during the public comment period, or grounds for the objection arose after the public comment period; and (2) the objection "is of central relevance to the outcome of the rule." 42 U.S.C. § 7607(d)(7)(B). An objection is "of central relevance" if it provides "substantial support for the argument that the regulation should be revised." *Coal. for Responsible Regulation, Inc. v. EPA*, 684 F.3d 102, 125 (D.C. Cir. 2012). The petitioner must show "the errors identified were so serious and related to matters of such central relevance to the rule that there is a substantial likelihood that the rule would have been significantly changed if such errors had not been made." *Union Oil Co. of Calif. v. EPA*, 821 F.2d 678, 683 (D.C. Cir. 1987). "If an objection fits within this exception, the consequences are

[4] *See* GAO Report to Congressional Requesters, *AIR POLLUTION Opportunities to Better Sustain and Modernize the National Air Quality Monitoring System* (Nov. 2020), available *at* https://www.gao.gov/products/GAO-21-38 (hereinafter "GAO Report").

weighty: EPA must grant reconsideration and conduct a new, full-dress, notice-and-comment rulemaking." *Alon Ref. Krotz Springs, Inc. v. EPA*, 936 F.3d 628, 647 (D.C. Cir. 2019). Where the standards for mandatory reconsideration are not met, EPA may still reconsider agency actions at its discretion.

ARGUMENT

I. EPA MUST RECONSIDER THE FINAL RULE IN LIGHT OF A NEW STUDY DEMONSTRATING SIGNIFICANT HEALTH RISKS TO ELDERLY PEOPLE IN THE UNITED STATES FROM LONG-TERM EXPOSURE TO OZONE.

The NAAQS must be based on air quality criteria that "accurately reflect the latest scientific knowledge useful in indicating the kind and extent of all identifiable effects on public health or welfare which may be expected from the presence of [a] pollutant in the ambient air." 42 U.S.C. 7408(a)(2). Furthermore, the primary standard must be set at a level that "allowing an adequate margin of safety, [is] requisite to protect the public health." 42 U.S.C. § 7409(b)(1). The primary standard must protect not only average healthy persons, but also sensitive or at-risk populations and groups, and must be designed to provide these groups with an adequate margin of safety "from the pollutant's adverse effects – not just known adverse effects, but those of scientific uncertainty or that research has not yet uncovered." *Am. Lung Ass'n,* 134 F.3d 388, 389 (D.C. Cir. 1998). Thus, the purpose of the "adequate margin of safety" is to protect against effects which have not yet been uncovered by research and effects whose medical significance is a matter of disagreement.

A new study by Yazdi, et al., titled *Long-Term Association of Air Pollution and Hospital Admissions Among Medicare Participants Using a Doubly Robust Additive Model*, demonstrates that the existing primary ozone level of 70 ppb is not sufficiently protective of the elderly population within the United States—a group that is already considered sensitive or at-risk—

with an adequate margin of safety.[5] Furthermore, the study suggests that additional standards for *long-term* exposure to ozone, which are not currently in place, may be necessary to protect public health within the elderly population.[6] The existence of this new evidence necessitates reconsideration of EPA's decision not to strengthen the existing NAAQS for ozone.

A. Petitioners Were Unable to Raise These Objections During the Public Comment Period Because This Study Had Not Yet Been Published.

The study by Yazdi, et al., was published on February 22, 2021 in the American Heart Association journal *Circulation*, after the close of the public comment period. State Petitioners were unable to raise these concerns during the public comment period because the study had not yet been released to the public. Thus, the grounds for State Petitioners' objections arose after the close of the public comment period.

B. The Identification of Significant New Threats to an At-Risk Population is of Central Relevance to EPA's Unlawful Decision to Retain the Existing NAAQS.

Given the new evidence revealed in this study about the significant negative impacts of long-term ozone exposure on the cardiovascular and respiratory health of elderly people in the United States, EPA must reconsider its decision to retain the existing NAAQS for ozone.

In addition to its overall conclusion that ozone is associated with an increased risk for four different cardiovascular and respiratory outcomes, the study found an association between tropospheric ozone exposure and hospital admissions for pneumonia among Medicare participants.[7] These adverse effects were based on exposure to levels below the current standard

[5] Yazdi, et al., *supra* note 2.

[6] *Id*.

[7] *Id*. at 7.

of 70 ppb.[8] Thus, this finding is of central relevance to EPA's contention in the final rule that the current level of 70 ppb protects public health with an adequate margin of safety.

The study also concluded that a standard that protects public health from long-term ozone exposure may be necessary given the effect of long-term ozone on respiratory outcomes.[9] Attainment with the current standard is determined based on the 3-year average of the fourth-highest daily maximum 8-hour average ozone concentration. This fails to account for or protect against the effects of long-term exposure to sustained levels that are below the 8-hour threshold of 70 ppb. By calling into question whether an 8-hour standard protects public health with an adequate margin of safety over the long term, the study is of central relevance to EPA's determination that the current primary standard adequately protects public health under the Clean Air Act.

II. EPA SHOULD RECONSIDER ITS DECISION IN THE FINAL RULE NOT TO REOPEN THE AIR QUALITY REVIEW TO ENABLE THE AGENCY, CASAC, AND THE PUBLIC TO FULLY CONSIDER RECENT EPIDEMIOLOGIC STUDIES LINKING OZONE EXPOSURE TO NEGATIVE HEALTH EFFECTS.

Health effects literature that either became available after the arbitrarily truncated Integrated Science Assessment cut-off date, or that was available but not reviewed in the Science Assessment and Policy Assessment, demonstrates the need for a primary ozone standard below 70 ppb to protect public health with an adequate margin of safety. State Petitioners brought this literature to EPA's attention in their comments on EPA's August 14, 2020 Notice of Proposed Rulemaking.[10] Specifically, State Petitioners commented that sixteen recent epidemiologic

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[8] *Id*. at 2.

[9] *Id*. at 11.

[10] Letter from Attorneys General of New York, California, Connecticut, the District of Columbia, Illinois, Maryland, Massachusetts, New Jersey, Oregon, Pennsylvania, Rhode Island, Vermont, Washington, and Wisconsin, and the Corporation Counsel of the City of New York to EPA Docket Center (Oct. 2, 2020); posted Oct. 2, 2020 at:

studies examining respiratory, cardiovascular, and mortality endpoints that have considered co-pollutants have reported significant results for ozone impacts.[11]

Rather than fully considering these additional studies in adopting the Final Rule or "reopening the review of the air quality criteria to enable the EPA, the CASAC, and the public to consider them further," 85 Fed. Reg. at 87,262, EPA decided to give the studies "provisional consideration" in this review. In the agency's words, this meant it failed to accord them "in-depth critical review" on par with the studies that it considered in its Integrated Science Assessment. 85 Fed. Reg. at 87,262. Based on this abbreviated review, EPA concluded that the studies "do not materially change any of the broad scientific conclusions regarding the health and welfare effects of [ozone] in the ambient air made in the air quality criteria" and therefore that "reopening the air quality criteria review would not be warranted." 85 Fed. Reg. 87,262-63. Properly considered, however, the epidemiologic evidence of respiratory and cardiovascular effects and mortality at exposure levels allowed by the current primary standard demonstrates that the current standard is insufficiently protective, and therefore EPA should have reopened review of the air quality criteria to allow for full, not "provisional," consideration.[12]

For example, one study by Zu, et al., found that a 10 ppb increase in average daily 8-hour maximum ozone concentrations, starting at 40 ppb, increased the risk for asthma hospitalization by 4.7% for school aged children and 1.8% among young adults.[13] Another recent epidemiologic

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https://www.regulations.gov/comment/EPA-HQ-OAR-2018-0279-0435. The States' Original Comments are hereby incorporated by reference (hereinafter, States' Comments).

[11] *Id*. at 26-30.

[12] *Id*. 26-30.

[13] Zu K, Liu X, Shi L, et al. *Concentration-response of short-term ozone exposure and hospital admissions for asthma in Texas. Environment International*. 2017;104:139-145. doi:10.1016/j.envint.2017.04.006; *See also* States' Comments at 26.

study by Raza, et al. links short-term ozone exposure to cardiovascular and respiratory mortality, especially in individuals previously hospitalized for heart attacks.[14] EPA failed to address this study's conclusion that the existing standard fails to protect individuals with a history of heart attacks—a sensitive, at-risk population—with an adequate margin of safety. As a third example, EPA failed to discuss a recent study by Lim, et al. examining the link between long-term ozone exposure and mortality.[15] Despite the study's conclusions that long-term exposure to ozone is associated with increased risk for multiple causes of mortality, EPA chose not to fully consider this study in relation to the adequacy of the existing standard.[16]

Evidence from these studies, along with the remaining thirteen studies that State Petitioners brought to EPA's attention during the public comment period, demonstrates that the current 70 ppb primary standard will likely produce adverse health effects in a sizeable portion of the United States population.[17] This in turn indicates that the existing standard fails to protect the public health—particularly that of sensitive or at-risk groups and populations—with an adequate margin of safety. Had EPA fully considered the studies submitted during the public comment period, there is a substantial likelihood that EPA would have revised the primary ozone standard to be more protective of public health. At a minimum, EPA's decision in the Final Rule not to reopen the review of the air quality criteria to enable EPA, the CASAC, and the public to

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[14] Raza A, Dahlquist M, Lind T, Ljungman PLS. *Susceptibility to short-term ozone exposure and cardiovascular and respiratory mortality by previous hospitalizations*. Environ Health. 2018;17(1):37. Published 2018 Apr 13. doi:10.1186/s12940-018- 0384-z; *See also* States' Comments at 27-28.

[15] Lim CC, Hayes RB, Ahn J, et al. *Long-Term Exposure to Ozone and Cause-Specific Mortality Risk in the United States*. Am J Respir Crit Care Med. 2019;200(8): 1022- 1031. doi:10.1164/rccm.201806-1161 OC; *See also* States' Comments at 28, 29.

[16] *Id*.

[17] *See* States' Comments at 26-30.

fully consider the studies was incorrect. EPA should remedy these errors now by exercising its discretion to convene reconsideration proceedings to engage in a reasoned review of these studies.

III. EPA SHOULD RECONSIDER THE FINAL RULE IN LIGHT OF A NEW REPORT FROM THE GOVERNMENT ACCOUNTABILITY OFFICE SUGGESTING THAT OZONE DATA RELIED UPON BY EPA IS INCOMPLETE.

EPA has not considered recommendations from a recent report by the Government Accountability Office, *AIR POLLUTION Opportunities to Better Sustain and Modernize the National Air Quality Monitoring System* (November 2020), addressing deficiencies in air monitoring data across the United States. The GAO Report, dated November 2020, was officially released to the public on December 7, 2020, after the comment period for the proposed rule closed.[18] In light of certain findings in the report, including the existence of gaps and quality assurance issues in ozone air monitoring data, EPA should have addressed concerns about the completeness of its ozone data in its Final Rule. EPA should grant reconsideration now to address: (a) whether the regional data it relied upon in conducting its exposure and risk analysis was complete, and (b) whether problems with data quality introduced a level of uncertainty into the exposure and risk analysis that warrants a larger margin of safety for the primary standard.

The GAO Report finds, among other things, that the national ambient air quality monitoring system overseen by EPA faces numerous challenges related to aging infrastructure.[19] According to EPA officials interviewed by GAO, aging air monitoring equipment creates vulnerabilities that directly affect the quality of the data.[20] This has led to several states

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[18] GAO Report, *supra* note 3.

[19] *Id.* at 28.

[20] *Id.*

invalidating their ozone data for 2015 and 2016—two of the years EPA relied on for the exposure and risk analysis in the ozone NAAQS review. In one example, a state agency reported that inadequate air conditioning in its air monitoring equipment shelters caused a week's worth of ozone data to be compromised.[21] Furthermore, the report suggests that regions where GAO conducted semi-structured interviews and reported deficiencies in data collection correspond to specific regions targeted by EPA's exposure and risk analysis.[22] For example, GAO interviewed officials in EPA's Region 6 offices in Dallas, which is also one of the eight metropolitan regions selected by EPA for inclusion in the exposure and risk analysis for ozone. In light of the fact that EPA officials in Dallas were interviewed, EPA should evaluate whether the monitoring data relied upon from that area was one of the problematic areas implicated by the GAO report.

All of these ozone-related monitoring concerns raised in the GAO Report potentially cast doubt on the accuracy of ozone data used by EPA in the exposure and risk analysis, which EPA ultimately used to "bridge the gap between the scientific assessments of the Integrated Science Assessment and the judgments required of the Administrator in his decisions on the current standard." 85 Fed. Reg. 87,264. By EPA's own account, the quantitative exposure and risk analyses it engages in are necessary to inform the review process. Therefore, EPA should evaluate the data gaps and monitoring issues identified in the GAO Report and, if warranted, reconsider its decision that the existing primary standard protect public health with an adequate margin of safety to satisfy the Clean Air Act's mandate.

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[21] *Id*. at 30.

[22] *Id*. at Appendix II: Objectives, Scope, and Methodology.

<u>RELIEF REQUESTED</u>

For the foregoing reasons, State Petitioners respectfully request that the Administrator immediately convene proceedings for reconsideration of the final action pursuant to 42 U.S.C. § 7607(d)(7)(B).

Dated: March 1, 2021

Respectfully Submitted,
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ATTACHMENT A

Circulation

ORIGINAL RESEARCH ARTICLE

Long-Term Association of Air Pollution and Hospital Admissions Among Medicare Participants Using a Doubly Robust Additive Model

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BACKGROUND: Studies examining the nonfatal health outcomes of exposure to air pollution have been limited by the number of pollutants studied and focus on short-term exposures.

METHODS: We examined the relationship between long-term exposure to fine particulate matter with an aerodynamic diameter <2.5 micrometers ($PM_{2.5}$), NO_2, and tropospheric ozone and hospital admissions for 4 cardiovascular and respiratory outcomes (myocardial infarction, ischemic stroke, atrial fibrillation and flutter, and pneumonia) among the Medicare population of the United States. We used a doubly robust method for our statistical analysis, which relies on both inverse probability weighting and adjustment in the outcome model to account for confounding. The results from this regression are on an additive scale. We further looked at this relationship at lower pollutant concentrations, which are consistent with typical exposure levels in the United States, and among potentially susceptible subgroups.

RESULTS: Long-term exposure to fine $PM_{2.5}$ was associated with an increased risk of all outcomes with the highest effect seen for stroke with a 0.0091% (95% CI, 0.0086–0.0097) increase in the risk of stroke for each 1-µg/m^3 increase in annual levels. This translated to 2536 (95% CI, 2383–2691) cases of hospital admissions with ischemic stroke per year, which can be attributed to each 1-unit increase in fine particulate matter levels among the study population. NO_2 was associated with an increase in the risk of admission with stroke by 0.00059% (95% CI, 0.00039–0.00075) and atrial fibrillation by 0.00129% (95% CI, 0.00114–0.00148) per ppb and tropospheric ozone was associated with an increase in the risk of admission with pneumonia by 0.00413% (95% CI, 0.00376–0.00447) per parts per billion. At lower concentrations, all pollutants were consistently associated with an increased risk for all our studied outcomes.

CONCLUSIONS: Long-term exposure to air pollutants poses a significant risk to cardiovascular and respiratory health among the elderly population in the United States, with the greatest increase in the association per unit of exposure occurring at lower concentrations.

Key Words: air pollution ■ atrial fibrillation ■ environment ■ epidemiology ■ ischemic stroke ■ myocardial infarction ■ pneumonia

Sources of Funding, see page XXX

https://www.ahajournals.org/journal/circ

Clinical Perspective

What Is New?

- Long-term exposure to air pollution was associated with an increased risk of hospital admissions with cardiovascular and respiratory outcomes on an additive scale among the elderly population of the United States.
- Each unit increase in levels of particulate matter, nitrogen dioxide, and ozone were associated with thousands of additional admissions each year.

What Are the Clinical Implications?

- Air pollution should be considered as a risk factor for cardiovascular and respiratory disease.
- The risk persists even at levels below current national and international guidelines.
- Patients should be conscious of the air quality in the region where they live to avoid harmful exposure over long periods of time.

Recent studies looking at the nonfatal health effects of air pollution have shifted their focus from short- to long-term exposure.[1–17] The effect estimates from studies on long-term exposure tend to be larger than studies on short-term exposure.[9,18] Furthermore, more studies are now exploring multiple air pollutants simultaneously in recognition of the fact that air pollution is a mixture of compounds with varying toxicities.[7,15,19] These changes suggest that current regulations may need to be amended. Some pollutants such as tropospheric ozone (O_3) do not have any national regulations on long-term exposure.

As research on the effect of long-term exposure to air pollution and health continues to proliferate, most of the current studies focus on mortality outcomes and estimate effects on a multiplicative scale, which are more difficult to interpret clinically because they depend on the distribution of other risk factors.[10,11,20,21] Cox proportional hazards models, for example, result in hazard ratios that are often interpreted interchangeably with relative risks, even though they are not the same.[22] Multiplicative models also make it more difficult to evaluate effect modification and identify vulnerable subpopulations. Cox proportional hazards models have multiplicative interactions built in to the model, which limits interpretability of further interactions in the model. Moreover, the Cox proportional hazards model provides an estimate of the effect of exposure that is conditional on the covariates and the baseline hazard. This makes use of those coefficients to estimate the attributable cases or risk problematic. In an additive model, the coefficients represent the risk difference as a result of exposure and the coefficients for interaction terms represent the additional risk difference in the subpopulation without reference to the baseline hazard or conditional on the distribution of the covariates. In addition, few studies use the propensity score–based doubly robust method that is often required to sway regulatory policy.[7,23–25] This limits knowledge on nonfatal outcomes and limits our ability to make convincing inferences to convince regulators. The studies that use causal methods often explore a single pollutant at a time and not the variety of compounds that comprise air pollution.

To address this gap, our study examines the relationship between average annual fine particulate matter (fine particulate matter with an aerodynamic diameter <2.5 micrometers [$PM_{2.5}$]), NO_2, and O_3, and 4 cardiovascular and respiratory hospitalization outcomes (myocardial infarction [MI]; ischemic stroke; atrial fibrillation and flutter; and pneumonia) using a doubly-robust additive model (DRAM) in fee-for-service Medicare beneficiaries across the contiguous United States from 2000 to 2016. In these models, we adjusted for multiple pollutants. We further evaluated effect measure modification (EMM) by demographic characteristics to identify particularly susceptible subpopulations.

METHODS

The data and materials used in this study will not be made available publicly or to other researchers because of restrictions in the data use agreement with the Centers for Medicare and Medicaid Services (CMS). However, CMS data are publicly available to researchers on completion of separate data use agreements. In this study, we examined the relationship between long-term exposure to (1) $PM_{2.5}$, NO_2, and O_3 and (2) first hospital admissions with several cardiovascular and respiratory diseases on an additive scale.

Study Population

Our full cohort consisted of all fee-for-service Medicare beneficiaries who were 65 years of age or older and who lived in the contiguous United States between 2000 and 2016. These data were derived from the Medicare denominator file and the Medicare Provider Analysis and Review file. We created a separate dataset for each outcome of interest. Patients entered the cohort on January 1 of the year after enrollment and were followed until they developed the outcome of interest, died, were censored, or reached the end of the follow-up time.

Exposure Assessment

$PM_{2.5}$, O_3, and NO_2 levels were derived from high-resolution spatiotemporal ensemble models, each of which combined estimates from 3 different machine learning algorithms, including a neural network, a gradient boosting machine, and a random forest.[26–28]

The models used hundreds of predictors including land use terms, chemical transport model predictions, meteorologic variables, and satellite measurements to estimate daily levels of the pollutants on a scale of 1 km × 1 km. The advantage of using these machine learning techniques is that they make no assumptions about the functional form of the relationships between the predictors and the outcome. The quality of the estimates was assessed using 10-fold cross-validation against measured values at Environmental Protection Agency monitoring sites across the United States. The resulting R^2 values of 0.89, 0.84, and 0.86 for the annual averages of $PM_{2.5}$, NO_2, and O_3, respectively, show excellent model performance.[26–28] Grid-cell values were averaged across zip codes. Exposure was assigned on the basis of the residential zip code of the beneficiary. Long-term exposure in our study is defined as the calendar year average of daily estimates.

Outcome Assessment

The dataset contains all hospital admissions for Medicare fee-for-service beneficiaries from 2000 through 2016. Medicare used *International Classification of Diseases, Ninth Revision* (*ICD-9*) codes through the end of the third quarter of 2015 and then switched to *International Classification of Diseases, Tenth Revision* (*ICD-10*). Primary discharge codes for myocardial infarction were defined as *ICD-9* codes 410.X0 and 410.X1 and *ICD-10* code I21 as the primary discharge code. Primary discharge codes for ischemic stroke were defined as *ICD-9* codes 433.X1, 434.X1, and 436, and *ICD-10* code I63 as the primary discharge code. Primary discharge codes for pneumonia were defined as *ICD-9* codes 003.22, 011.6, 055.1, 073.0, 115.05, 115.15, 115.95, 480, 481, 482, 483, 484, 485, 486, 487.0, 488.01, 488.11, 488.81, 516.3, 517.1, and 997.32, and *ICD-10* codes A01.03, A02.22, A20.2, A21.2,A22.1, A37.X1, A42.0, A43.0, A48.1, A54.84, A69.8, B01.2, B05.2, B06.81, B25.0, B37.1, B38.0,B39.0, B44.0, B44.1, B58.3, B59, B77.81, J15, J09.X1, J10.0, J11.0, J12, J13, J14, J17, J18, J84.2, J85.1, and J95.851 as primary discharge codes. Primary discharge codes for atrial fibrillation and flutter were defined as *ICD-9* code 427.3 and *ICD-10* code I48 as the primary discharge codes.

Covariate Assessment

We obtained data on individual-level covariates sex, race, age group, and Medicaid eligibility from the Medicare denominator file. We used data from the US Census and the American Community Survey to find zip code–level socioeconomic data: proportion of the population >65 years of age living below the poverty line, population density, median value of owner occupied properties, proportion of the population listed as Black, median household income, proportion of housing units occupied by the owner, proportion of the population identified as Hispanic, and proportion of the population >65 years of age who had not graduated from high school. Measured data were available for 2000 and 2010 through 2016. Data for all other years and missing values were obtained using linear interpolation and extrapolation.

The lung cancer hospitalization rate in each zip code was used as a proxy for smoking and was derived from Medicare Provider Analysis and Review.[29–31]

We derived zip code–level data on mean body mass index and the smoking rate from the Behavioral Risk Factor Surveillance System. Behavioral Risk Factor Surveillance System data were collected at the county level and then linked to relevant zip codes and temporally interpolated using linear regression to fill in missing values.

We obtained zip code–level data on several access-to-care variables: proportion of Medicare beneficiaries with at least 1 hemoglobin A1c test in a year; proportion of elderly diabetic beneficiaries who had a lipid panel test in a year; proportion of beneficiaries who had an eye examination in a year; proportion of beneficiaries with at least 1 ambulatory doctor visit in a year; and proportion of female beneficiaries who had a mammogram during a 2-year period. These were obtained from the Dartmouth Atlas of Health Data. Data were collected at the hospital service area–level and linked to the relevant zip code. Missing values were filled in using linear interpolation. We also included region of residence to account for geographic differences and distance to hospital as a variable to measure access to health care. The distance to the nearest hospital was calculated from the centroid of the residential zip code of the patient. Hospital locations across the United States were derived from an ArcGIS dataset.[32]

Observations with missing exposure or covariate information were assumed to be missing at random and were excluded from further analysis. These represented less than 1% of the data.

Statistical Analysis

We examined the relationship between long-term exposure to $PM_{2.5}$, NO_2, O_3, and admissions with cardiovascular and respiratory outcomes using a doubly robust additive model (DRAM). Specifically, confounding is accounted for through 2 mechanisms: first, in inverse probability weights of exposure; and second, by adjustment in the outcome regression model. If either of the models is correctly specified, the estimated coefficient is unbiased.[33] The equation for this model is as follows:

$$Pr\left(Admissions_{ij}\right) = \beta_0 + \beta x_{ij} + s\left(v_{ij}, \gamma\right)$$

$$\begin{aligned}
&= \beta_0 + \beta x \ (pollutant\ of\ \ interest)_{ij} + age + race + sex + year \\
&+ region\, of\ residence + Medicaid\ eligibility + distance\ to \\
&nearest\ hospital + other\ pollutant\ 1 + other\ pollutant\ 2 \\
&+ pct_eye_exam + pct_lipid_panel + pct_mammogram \\
&+ pct\ _in_poverty + median\, house\, value + pct_below_ \\
&high_school_education + median\, household\ income \\
&+ pct_pop_black + pct_pop_hispanic + population\, density \\
&+ lung\, cancer\ rate + pct\ owner\ occupied\ housing + pct_ \\
&ambulatory_care_appt + pct_HgbA1c_exam \\
&+ mean\, BMI + smoking\, rate
\end{aligned}$$

where $Pr\ (Admissions_{ij})$ represents the probability of the outcome for individual i in year j, x represents the exposure, v represents the vector of covariates, and γ represents the parameterization (eg, coefficients) of the covariates. In this case, the parametrization was assumed to be linear. This equation is weighted using stabilized inverse probability weighting for exposure from the following formula:

$$SW_{ij} = \frac{f(x)}{f(x|v)}$$

where x represents the exposure and v represents the covariates. In this case, we defined $f(x|v)$ as the probability density of the exposure on the basis of a linear regression with the exposure of interest as the outcome and the covariates and other pollutants as the predictors. For example, in the model for $PM_{2.5,}$ we adjusted for individual and socioeconomic and behavioral covariates as well as O_3 and NO_2. The same covariates and other pollutants were adjusted for in the outcome regression model as well.

Assuming that (1) the underlying true outcome regression model follows the additive structure $Pr(Admissions_{ij}) = \beta_0 + \beta x_{ij} + s'(v_{ij}, \gamma)$, where s' may or may not be the same as s; and (2) either the inverse probability weighting or the functional form of s is correctly specified (ie, $s = s'$), the resulting risk difference estimate is consistent. To account for outliers, we trimmed the weights: values >99th percentile were given the value at the 99th percentile and values <1st percentile were given the value at the 1st percentile.

We ran 200 bootstraps of the weighted outcome regression for each analysis. The median value was used as the coefficient of interest and the 2.5 percentile and 97.5 percentile constituted the 95% CI.

We evaluated effect modification by sex, race, Medicaid eligibility, and age group using stratification. The coefficients from each stratum were compared with one another to identify vulnerable subpopulations. We also conducted a subgroup analysis on person-years with pollutant levels below international regulations. For $PM_{2.5,}$ we restricted to individuals with levels <10 μg/m³ for all years; for NO_2, we restricted to individuals with levels <20 ppb for all years; and for O_3, we restricted to individuals with levels <40 ppb for all years with effect measure modification analyses for these subsets as well. As a sensitivity analysis, we calculated E-values for our main results. E-values measure the magnitude of the relationship a hypothetical unmeasured confounder would have to have with both the exposure and the outcome to fully account for the effect estimate that has been found.[34] A schematic of how the study was constructed and carried can be seen in Figure 1.

All data cleaning and statistical analyses were conducted in R Statistical Software (version 3.6.1) and the inverse probability weighting and outcome regression estimates were obtained using the "biglm" package.[35] Data cleaning and analysis was completed on the Research Computing Environment as part of Research Computer at Harvard University Faculty of Arts and Sciences.

This study was approved by the Harvard School of Public Health Institutional Review Board.

RESULTS

The cohort consisted of 63 006 793 Medicare beneficiaries who used the fee-for-service program from 2000 to 2016 in the contiguous United States. Demographic characteristics for these individuals can be seen in Table 1. There are slightly more women than men, and most participants are White. Of the observations used in the analyses, 85% were not Medicaid-eligible, and about half were between 64 and 75 years of age. The majority of the observations came from the southern and midwestern regions of the United States.

Table 2 shows the distribution of air pollutants across the contiguous United States from 2000 to 2016. Annual average levels of $PM_{2.5}$ and NO_2 were generally low, below the Environmental Protection Agency annual standard of 12 μg/m³ and 53 ppb. O_3 does not have an annual standard level, but the levels are below the daily standard of 70 ppb.[36] This distribution also reveals that our lower exposure analysis, which was subset to only include individuals with lower values, was largely consistent with prevailing levels that a person might typically experience.

The distribution of weights across person-years in 1 of our datasets (MI) can be seen, after trimming, in Table 3. The distribution across years is largely consistent, and no observation received extreme weight values.

The results of our primary analysis can be seen in Figure 2A and Table 4. Long-term exposure to $PM_{2.5}$ was associated with a statistically significant increase in the risk of all outcomes. This translated to thousands of hospital admissions attributable to air pollution per year. For example, there were 2536 (95% CI, 2383–2691) additional admissions for each 1 μg/m³ increase in $PM_{2.5}$ for ischemic stroke, 637 (95% CI, 483–814) for myocardial infarction, 1575 (95% CI, 1426–1691) for atrial fibrillation, and 2489 (95% CI, 2245–2738) for pneumonia. Long-term exposure to

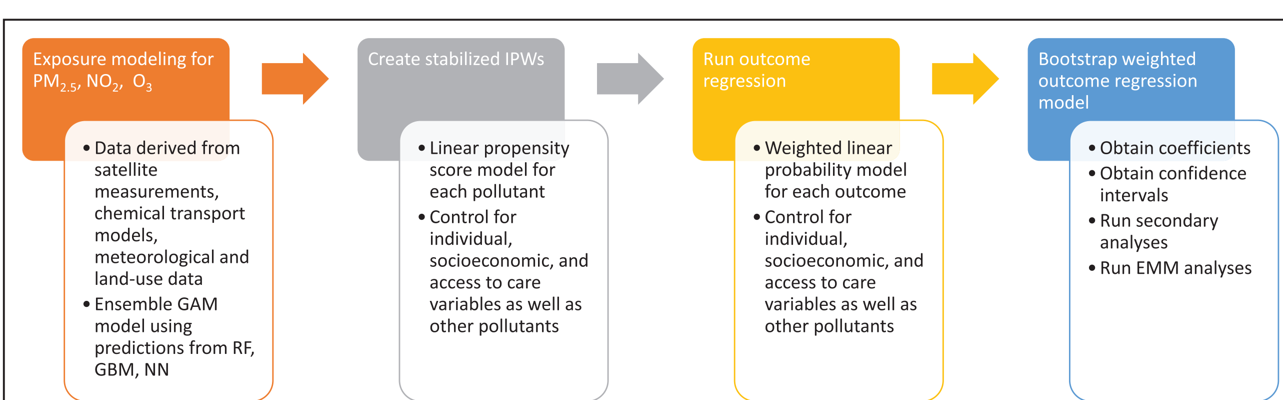

Figure 1. Study design schematic.
Flow chart of how study was conducted step-by-step.

Table 1. Demographic Characteristics of Medicare Fee-for-Service Patients

Variable	N (%)
Individual characteristics (N=63 006 793)	
Sex	
Female	34 725 250 (55.11)
Male	28 281 543 (44.89)
Race	
White	53 207 613 (84.45)
Black	5 511 770 (8.75)
Other	4 287 410 (6.80)
Demographic characteristics, person-years (N=538 173 801)	
Medicaid eligibility	
Yes	76 042 269 (14.13)
No	462 131 532 (85.87)
Age group, y	
65–74	277 788 354 (51.62)
75–84	181 809 593 (33.78)
≥85	78 575 854 (14.60)
US region	
Northeast	105 812 685 (19.66)
Midwest	132 107 154 (24.55)
South	209 831 299 (38.99)
West	90 422 663 (16.80)

NO_2 was associated with an increased risk of stroke and atrial fibrillation and showed a negative effect for admissions of MI and pneumonia. Long-term exposure to O_3 led to mixed results; it increased the risk of pneumonia admissions, but the coefficient was negative for stroke and atrial fibrillation. The E-values suggested that the $PM_{2.5}$ model was the most robust to unmeasured confounding (the E-values are reported on the multiplicative scale). This meant that if an unmeasured confounder exits, it would need to have a stronger relationship with both the exposure and the outcome to fully explain away the harmful effects we observed. In general, the trend showed higher E-values for relationships where we found harmful effects versus those that had negative coefficients.

We further looked at hospital admissions for individuals who had low pollutant concentration throughout the follow-up period (Figure 2B). For all pollutants, the association of hospital admissions increased for cardiovascular and respiratory outcomes with larger effect size estimates. This shows that the greatest increase in the risk of admissions per unit change in exposure occurs at lower concentrations of air pollutants.

One of the advantages of our additive model is that effect measure modification can be measured on an additive scale. We assessed effect modification by Medicaid eligibility, sex, race, and age group for all of our pollutants and outcomes. Figure 3A shows the results for this analysis and MI. The results vary by pollutant. For $PM_{2.5}$, older beneficiaries were at a higher risk of admission as compared with younger beneficiaries, and White individuals had a higher risk of admission as compared with Black individuals. For NO_2, the stratified analysis was generally negative. However, Black individuals were at a higher risk than White individuals. For O_3, those who were Medicaid-eligible, male, and younger had a higher probability of hospital admission with an MI as compared with those who were not Medicaid-eligible, female, and older, respectively.

The results of the EMM analysis for ischemic stroke can be seen in Figure 3B. For $PM_{2.5}$, older participants had a significantly higher risk of admission than younger individuals. For NO_2, those who were not Medicaid-eligible were at a higher risk than those who were Medicaid-eligible and Black individuals were at a higher risk than White individuals. The results for the stratified ozone analysis showed negative coefficients.

Figure 3C shows the results of the EMM analysis for atrial fibrillation and flutter. For $PM_{2.5}$, those not Medicaid-eligible, White, and older were at increased risk of admission. Similarly, for NO_2, those who were not Medicaid-eligible and older had a higher probability of being admitted with atrial fibrillation than those who were Medicaid-eligible and younger. For ozone, the stratified analyses showed a generally protective effect.

The results for the EMM analysis of pneumonia are shown in Figure 3D. For $PM_{2.5}$, those who were Medicaid-eligible, Black, or in older age groups are at increased risk of admission with pneumonia as compared with those who are not. In contrast, the stratified analyses for NO_2 and pneumonia show a negative effect estimate for most subsets. Last, exposure to ozone was associated with a higher probability of admission with atrial fibrillation and flutter among those who are Medicaid-eligible, White, or in older age groups.

Table 2. Exposure Distribution of Pollutants Across Person-Years

Variable	Minimum	10th Percentile	25th Percentile	Mean	Median	75th Percentile	90th Percentile	Maximum
$PM_{2.5}$ (μg/m³)	0.01	6.36	8.11	10.21	10.05	12.29	14.32	30.92
NO_2 (ppb)	0.01	8.13	11.51	19.50	17.44	25.88	33.88	127.63
O_3 (ppb)	18.31	33.88	36.56	38.77	38.75	40.92	43.74	65.09

O_3 indicates tropospheric ozone; and $PM_{2.5}$, fine particulate matter with an aerodynamic diameter <2.5 micrometers.

Table 3. Distribution of Inverse Probability Weights Across Years for Myocardial Infarction, After Trimming

Pollutant and year	Minimum	10th	25th	Mean	Median	75th	90th	Maximum
$PM_{2.5}$								
2000	0.159	0.342	0.614	1.301	1.024	1.386	2.319	8.414
2001	0.159	0.359	0.652	1.285	1.031	1.366	2.212	8.414
2002	0.159	0.457	0.746	1.320	1.059	1.360	2.199	8.414
2003	0.159	0.462	0.731	1.264	1.041	1.341	2.054	8.414
2004	0.159	0.543	0.806	1.306	1.072	1.359	2.089	8.414
2005	0.159	0.425	0.696	1.258	1.030	1.339	2.112	8.414
2006	0.159	0.645	0.873	1.292	1.076	1.337	1.980	8.414
2007	0.159	0.563	0.812	1.275	1.060	1.325	1.996	8.414
2008	0.159	0.737	0.973	1.325	1.104	1.370	1.992	8.414
2009	0.159	0.688	0.969	1.354	1.116	1.409	2.095	8.414
2010	0.159	0.631	0.929	1.299	1.102	1.369	1.987	8.414
2011	0.159	0.722	0.999	1.342	1.119	1.396	2.023	8.414
2012	0.159	0.619	0.942	1.396	1.116	1.459	2.243	8.414
2013	0.159	0.611	0.929	1.469	1.112	1.530	2.537	8.414
2014	0.159	0.537	0.893	1.387	1.098	1.453	2.329	8.414
2015	0.159	0.523	0.855	1.442	1.088	1.522	2.598	8.414
2016	0.159	0.421	0.750	1.536	1.032	1.640	3.122	8.414
All	0.159	0.512	0.836	1.346	1.084	1.402	2.217	8.414
NO_2								
2000	0.094	0.382	0.800	1.405	1.040	1.398	2.434	10.817
2001	0.094	0.359	0.790	1.393	1.034	1.369	2.371	10.817
2002	0.094	0.409	0.771	1.338	1.021	1.326	2.256	10.817
2003	0.094	0.395	0.754	1.321	1.018	1.310	2.212	10.817
2004	0.094	0.517	0.801	1.322	1.020	1.301	2.136	10.817
2005	0.094	0.485	0.778	1.318	1.017	1.309	2.160	10.817
2006	0.094	0.527	0.778	1.292	1.015	1.283	2.031	10.817
2007	0.094	0.502	0.725	1.292	0.993	1.283	2.076	10.817
2008	0.094	0.546	0.769	1.275	1.000	1.259	1.988	10.817
2009	0.094	0.542	0.759	1.266	0.994	1.250	1.996	10.817
2010	0.094	0.574	0.776	1.283	0.997	1.252	1.995	10.817
2011	0.094	0.599	0.794	1.290	1.003	1.260	2.018	10.817
2012	0.094	0.670	0.837	1.316	1.014	1.269	1.966	10.817
2013	0.094	0.611	0.791	1.316	1.006	1.264	1.997	10.817
2014	0.094	0.598	0.796	1.331	1.009	1.255	2.062	10.817
2015	0.094	0.625	0.804	1.337	1.011	1.259	2.048	10.817
2016	0.166	0.628	0.808	1.447	1.021	1.329	2.297	10.817
All	0.094	0.548	0.786	1.327	1.014	1.292	2.115	10.817
O_3								
2000	0.177	0.490	0.722	1.034	0.910	1.066	1.486	6.173
2001	0.177	0.584	0.807	1.072	0.952	1.084	1.486	6.173
2002	0.177	0.615	0.834	1.073	0.956	1.089	1.454	6.173
2003	0.177	0.573	0.830	1.042	0.955	1.075	1.391	6.173
2004	0.177	0.512	0.775	1.035	0.943	1.066	1.401	6.173
2005	0.177	0.607	0.808	1.062	0.948	1.067	1.432	6.173

(Continued)

Table 3. Continued

Pollutant and year	Minimum	10th	25th	Mean	Median	75th	90th	Maximum
2006	0.177	0.537	0.750	1.010	0.921	1.038	1.393	6.173
2007	0.177	0.563	0.798	1.075	0.951	1.092	1.505	6.173
2008	0.177	0.575	0.808	1.060	0.945	1.051	1.391	6.173
2009	0.177	0.413	0.774	1.061	0.954	1.120	1.506	6.173
2010	0.177	0.692	0.844	1.168	0.960	1.127	1.651	6.173
2011	0.177	0.648	0.832	1.113	0.953	1.077	1.514	6.173
2012	0.177	0.675	0.865	1.115	0.963	1.113	1.536	6.173
2013	0.177	0.707	0.905	1.199	0.990	1.202	1.682	6.173
2014	0.177	0.705	0.895	1.128	0.974	1.131	1.514	6.173
2015	0.177	0.709	0.905	1.132	0.981	1.148	1.539	6.173
2016	0.177	0.699	0.896	1.104	0.970	1.106	1.472	6.173
All	0.177	0.595	0.829	1.088	0.956	1.098	1.491	6.173

O_3 indicates tropospheric ozone; and $PM_{2.5}$, fine particulate matter with an aerodynamic diameter <2.5 micrometers.

When looking at the EMM analysis for those exposed to lower concentrations, the harmful effects seen previously persisted across strata for all pollutants and across outcomes (Figure 4). For MI, $PM_{2.5}$ and NO_2 were associated with an increased risk of the admissions for men, elderly adults, and those who were Medicaid-eligible as compared with those who were not. O_3 increased the risk of hospital admission with MI for men and Black individuals (Figure 4A).

For ischemic stroke (Figure 4B), $PM_{2.5}$ increased the risk of admission for those who were Medicaid-eligible, women, or elderly. For NO_2, the more vulnerable subpopulations were those who were Medicaid-eligible, Black, or elderly. For O_3, those who were Medicaid-eligible, women, or White were at increased risk of stroke.

$PM_{2.5}$ and NO_2 increased the risk of atrial fibrillation and flutter among those who were White and very elderly adults, as compared with those who were not. O_3 was found to particularly increase the risk of admission among those who were not Medicaid-eligible and who were White.

For pneumonia, all pollutants increased the risk of hospital admissions among those who were Medicaid-eligible and elderly as compared with those who were not. On the other hand, $PM_{2.5}$ was associated with an increased risk of atrial fibrillation among those who were White while O_3 was associated with an increased risk among those who were Black.

DISCUSSION

The results of our study showed several important trends. First, $PM_{2.5}$ was associated with an increased risk of hospital admissions with all of our studied outcomes. This was particularly true for elderly individuals who were at increased risk. Second, NO_2 was associated with an increased the risk of stroke and atrial fibrillation and flutter. This trend was largely consistent across strata. However, O_3 was negative in the cardiovascular outcomes but was associated with an increased probability of pneumonia. This is consistent with other literature linking ozone to respiratory outcomes.[37–39] This seemed to suggest that NO_2 and O_3 confound each other's effects or may be confounded by an unknown or unmeasured variable. Support for this comes from the pattern of NO_2, showing positive associations for outcomes where O_3 shows negative associations and vice versa. The partial correlation coefficient between the 2 in our data was −0.186, which shows a moderate negative correlation after adjusting for all other variables. Moreover, the E-values tended to be smaller for the negative coefficients, which implies that those relationships are more susceptible to unmeasured confounding as compared with the harmful effects that were less susceptible to unmeasured unconfounding. It is also likely that there is greater exposure measurement error at higher concentrations because the models were primarily trained on monitoring data at lower concentrations. This could account for the inconsistent results in the full range of exposure analyses.

At lower concentrations, all pollutants increased the probability of hospital admissions with larger effect estimates than the primary results. That the negative effects of NO_2 and O_3 disappear when restricted to pollution concentrations in the more normal range suggests that those effects in the full analysis may be attributable to outlier exposures, more exposure error, and stronger negative correlations between high NO_2 and low O_3 than for more common concentrations. The higher effect sizes for risk of cardiovascular and respiratory outcomes at the lower end of air pollution exposure is consistent with several other studies in this population looking at health effects at lower concentrations.[7,21,40,41] In the subgroup analyses, $PM_{2.5}$ and NO_2 were associated with an increased risk of

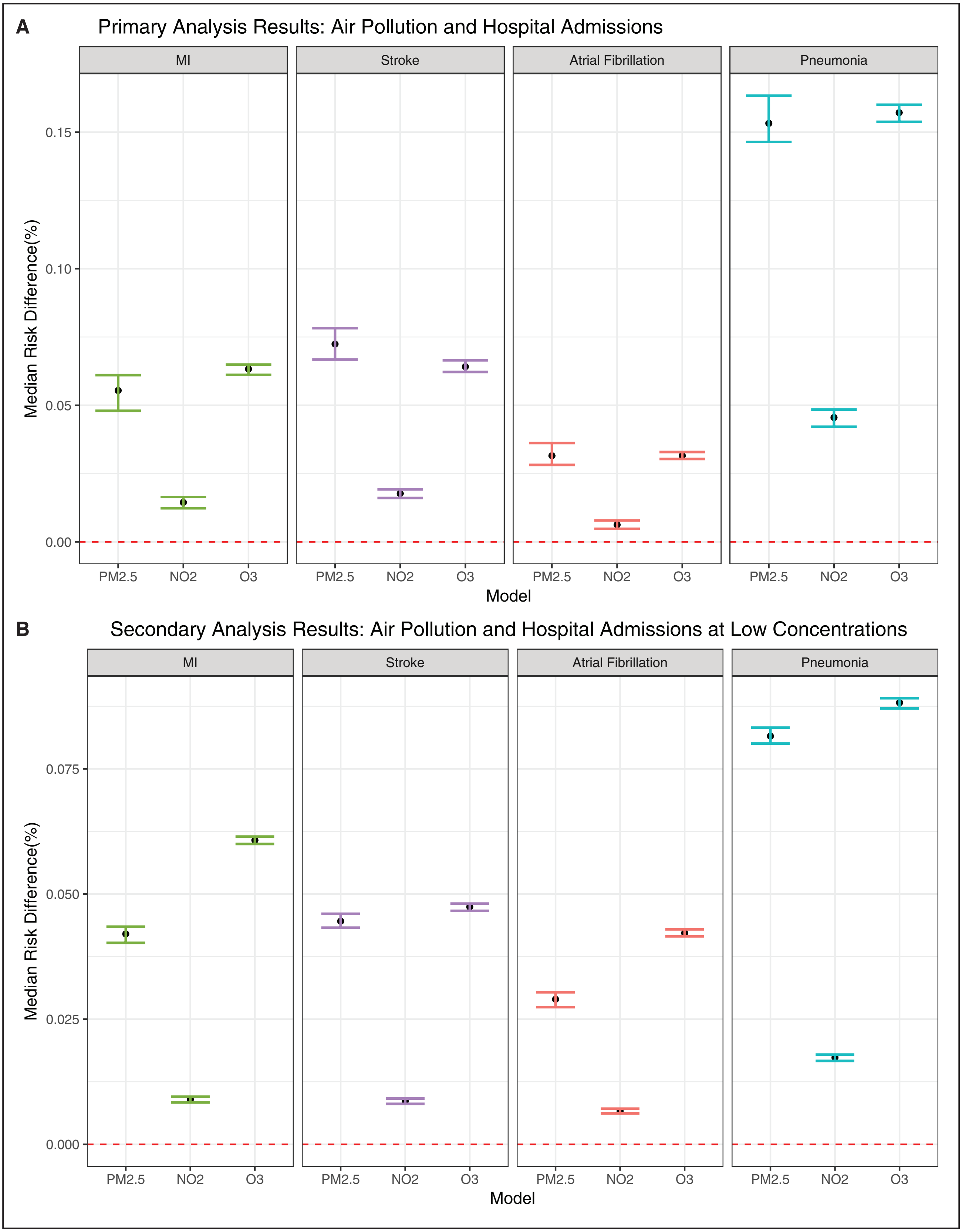

Figure 2. Primary and secondary analyses results.
A, Primary analyses results: median risk difference (95% CI) for each unit increase in air pollutants and hospital admission with cardiovascular and respiratory outcomes across the full range of exposure. **B**, Secondary analyses results: median risk difference (95% CI) for each unit increase in air pollutants and hospital admission with cardiovascular and respiratory outcomes at lower concentrations of exposure.

Table 4. Main Analyses Results and Sensitivity Analyses (E-Values)

Outcome	Pollutant	Median risk difference (%)	Lower 95% CI (%)	Upper 95% CI (%)	Attributable increase in the number of cases* (95% CI)	E-value (multiplicative scale)
Myocardial infarction	$PM_{2.5}$ (μg/m³)	0.00231	0.00175	0.00295	637 (483–814)	1.0160
	NO_2 (ppb)	−0.00084	−0.00103	−0.00067	N/A†	1.0096
	O_3 (ppb)	−0.00024	−0.00052	0.00002	N/A†	1.0050
Stroke	$PM_{2.5}$ (μg/m³)	0.00914	0.00859	0.00970	2536 (2383–2691)	1.0323
	NO_2 (ppb)	0.00059	0.00039	0.00075	163 (108–208)	1.0080
	O_3 (ppb)	−0.00278	−0.00300	−0.00246	N/A†	1.0175
Atrial fibrillation and flutter	$PM_{2.5}$ (μg/m³)	0.00569	0.00515	0.00611	1575 (1426–1691)	1.0253
	NO_2 (ppb)	0.00129	0.00114	0.00148	357 (316–410)	1.0119
	O_3 (ppb)	−0.00072	−0.00091	−0.00047	N/A†	1.0088
Pneumonia	$PM_{2.5}$ (μg/m³)	0.00909	0.00820	0.01004	2489 (2245–2738)	1.0322
	NO_2 (ppb)	−0.00134	−0.00158	−0.00110	N/A†	1.0121
	O_3 (ppb)	0.00413	0.00376	0.00447	1131 (1030–1224)	1.0215

*Per one-unit increase per year in pollutants.
†Negative values on a probability scale are not logical. As such, the attributable number of cases were not calculated.
O_3 indicates tropospheric ozone; and $PM_{2.5}$, fine particulate matter with an aerodynamic diameter <2.5 micrometers.

hospitalization for cardiovascular outcomes among very elderly adults in both the full exposure range and the lower concentration range. Those who were Medicaid eligible were at increased risk of pneumonia attributable to $PM_{2.5}$ and O_3 in both the full and low concentration groups. Individuals who identified as White were at greater risk of atrial fibrillation attributable to NO_2 than those who identified as Black. In contrast, those who identified as Black were at greater risk of stroke attributable to NO_2 than those who identified as White.

The existing literature on the nonfatal health effects of long-term exposure to air pollution shows mixed results depending on the pollutants and the population studied and the method used. A previous study in the same population that focused on the southeastern region of the United States found both $PM_{2.5}$ and O_3 to be risk factors for MI, stroke, and pneumonia on the multiplicative scale, while we found ozone to be negative for ischemic stroke on an additive scale here in the full exposure model,[7] but a risk factor at more modest concentrations. Researchers working with the ESCAPE (European Study of Cohorts for Air Pollution Effects) data looked at several air pollutants and the incidence of acute coronary disease between 1997 and 2007 in Finland, Sweden, Denmark, Germany, and Italy. Both $PM_{2.5}$ and NO_2 were nonsignificantly associated with an increased hazard of acute coronary events in an adjusted model.[10] They further found that neither $PM_{2.5}$ nor NO_2 were significantly associated with stroke incidence in the ESCAPE cohort.[11] This contrasts with our results that found $PM_{2.5}$ to be harmful and NO_2 to be negative for MI, and both pollutants to be harmful for stroke (including all observations, though both were harmful for all outcomes at lower concentrations). Among a cohort of women enrolled in the Women's Health Initiative , long-term exposure to $PM_{2.5}$ was associated with a higher hazard of stroke, though no relationship was found with MI.[42] A case-control study nested in the Worcester Heart Attack cohort found positive but nonsignificant association between long-term exposure to $PM_{2.5}$ and acute MI overall.[12] A study in the Danish, Diet, Cancer and Health cohort between 1993 and 2006 looked at ischemic stroke and found a nonsignificant increase in the hazard of the incidence of disease with long-term exposure to NO_2.[43] In a study among the EPIC (European Prospective Investigation into Cancer and Nutrition) cohort in Greece, NO_2 was not associated with an increase in the hazard of stroke and ischemic heart disease.[13] A study done in South Korea examining the effect of long-term exposure to air pollutants, including $PM_{2.5}$ and NO_2, found similar results to ours. $PM_{2.5}$ increased the hazard of MI and ischemic stroke, in both single and multipollutant models, and ozone showed a decreased hazard of both conditions. However, unlike our study, they found NO_2 to increase the risk of MI.[15] A study of British patients between 2003 and 2007 looked at air pollutants including NO_2 and O_3 and incident cases of cardiovascular disease, and researchers found largely nonsignificant results for MI, stroke, and arrythmia in their single pollutant model.[16] Last, a meta-analysis of long-term exposure to $PM_{2.5}$ as a risk factor for stroke found a 6.4% (95% CI, 2.1–10.9%) increase in the hazard of admission for each 5-μg/m³ increase in $PM_{2.5}$ levels which is consistent with our results of an increased probability of stroke.[17]

The harm caused by air pollution to the cardiovascular and respiratory systems is generally attributed to its ability to increase inflammation and oxidative stress and disrupt the coagulation cascade.[44–47] In SEBAS (Social

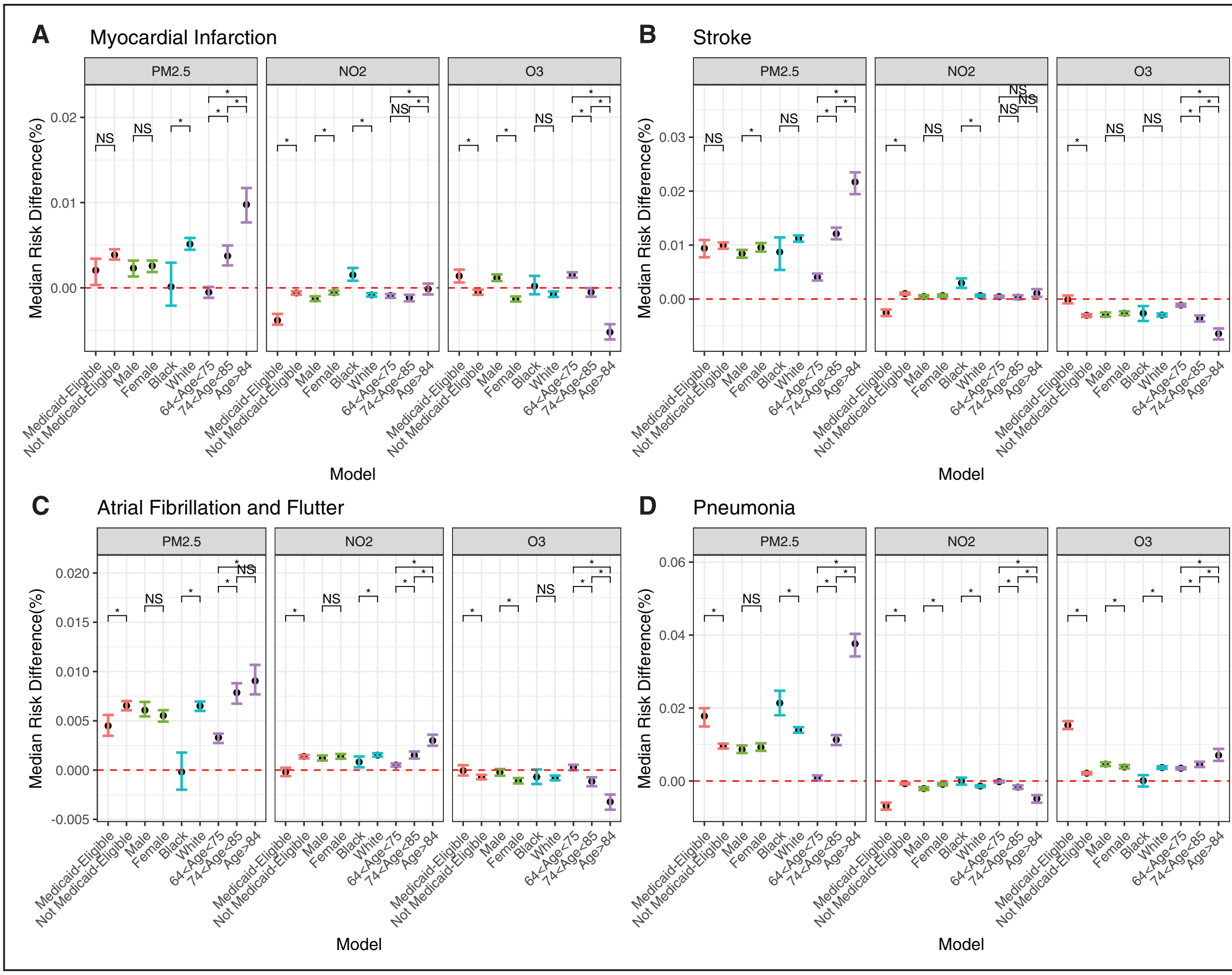

Figure 3. Effect measure modification analyses: full range of exposure concentration.
Effect measure modification analyses: median risk difference (95% CI) for each unit increase in air pollutants and hospital admission with myocardial infarction (**A**), stroke(**B**), atrial fibrillation (**C**), and pneumonia (**D**) across the full range of exposure, within strata. Pairwise comparisons of coefficients were conducted. *Statistically significant differences (*P*<0.05). NO_2, nitrogen dioxide; NS, nonsignificant difference; O_3, tropospheric ozone; and $PM_{2.5}$, fine particulate matter with an aerodynamic diameter <2.5 micrometers.

Environment and Biomarkers of Aging Study) in Taiwan, changes in annual $PM_{2.5}$ and O_3 levels were associated with higher levels of systolic and diastolic blood pressure, total cholesterol, fasting glucose, hemoglobin A1c, and neutrophils. NO_2 was associated with all, as well as elevated levels of interleukin-6 . Lipids, glucose levels, and inflammatory biomarkers are all risk factors for cardiovascular disease.[48] Moreover, in the ESCAPE study, participants showed decreased lung function, as measured by forced expiratory volume in 1 second and forced vital capacity, in response to NO_2, which can be a marker of respiratory disease.[49]

Our study has numerous strengths that make the results particularly compelling. First, the coefficients obtained are risk differences and do not require transformation to be interpretable. Furthermore, the coefficients are on the additive scale. This is particularly helpful for the stratified analyses in which the additional number of cases attributable to the variable can be identified directly and are of greater public health importance.[50] Second, this study uses a causal modeling approach. Randomized trials produce causal estimates because randomization renders intention-to-treat independent of other predictors of outcome. Propensity score methods try to achieve the same result. The inverse probability weights create a pseudo population in which exposure is independent from the measured confounders.[51] If all confounders are measured and the model for the dependence of exposure on confounders (used to create the weights) is correct, this approach will similarly produce a causal estimate. Given that we also control for the covariates, our approach is also doubly robust, meaning that if either the inverse probability weighting model or the outcome model are correctly specified, our estimates are unbiased and causal. Furthermore, we derived our estimates and CIs empirically using bootstrapping. In our model, we account for multiple air pollutants, which were estimated from prediction models on a fine scale,

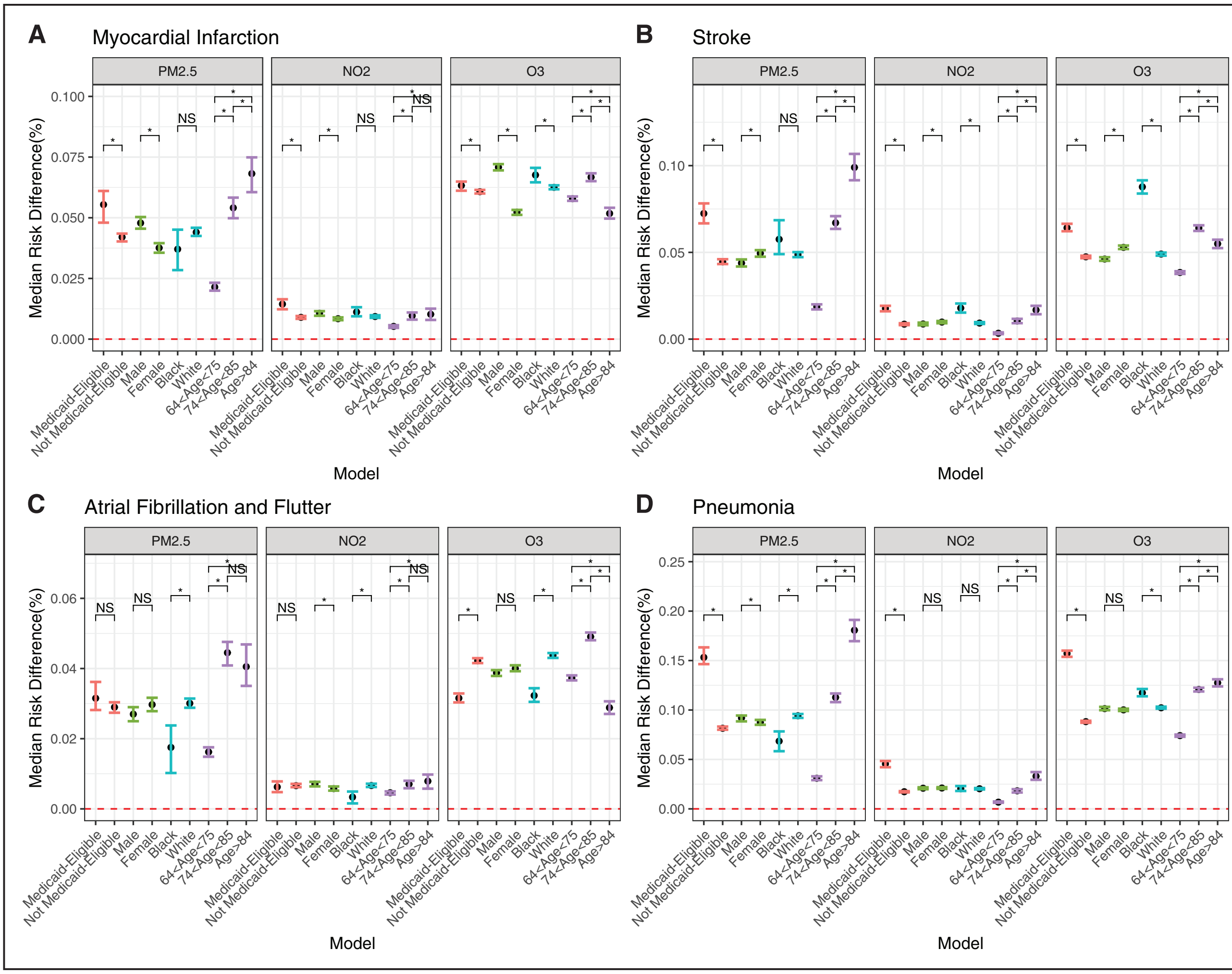

Figure 4. Effect measure modification analyses: lower range of exposure concentration.
Median risk difference (95% CI) for each unit increase in air pollutants and hospital admission with myocardial infarction (**A**), stroke(**B**), atrial fibrillation(**C**), and pneumonia (**D**) at lower exposure concentrations, within strata. Pairwise comparisons of coefficients were conducted. *Statistically significant differences (*P*<0.05). NO_2, nitrogen dioxide; NS, nonsignificant difference; O_3, tropospheric ozone; and $PM_{2.5}$, fine particulate matter with an aerodynamic diameter <2.5 micrometers.

allowing us to identify the more toxic components of the air pollution mixture while adjusting for others. Last, our study focuses on long-term effects, which have not been as thoroughly examined, but may be of greater importance in terms of the health effect of air pollution. This is particularly important to reaffirm, or in some cases establish, the need for long-term guidelines, such as for O_3 which does not even have national annual guidelines. Our study suggests that long-term O_3 guidelines may be particularly necessary given the effect of long-term ozone on respiratory outcomes.

Our approach also had several limitations. The causal methodology we use relied on the strong assumption of no unmeasured confounding which is not testable. Hence, causality is not proven, and can only be an interpretation, which should include support from toxicology. We did, however, calculate E-values to see the strength of the relationship a hypothetical unmeasured confounder would have to have with both the exposure and the outcome to fully account for the results we found. Moreover, we chose a more conservative approach and controlled for lung cancer rate as a proxy for smoking. However, air pollution is itself a risk factor for lung cancer. As such, we may be overcontrolling for smoking and underestimating the true effect size. We also assumed that loss to follow-up among our population was unrelated to air pollution. In addition, Medicare is an administrative database and billing codes could leave the door open to potential outcome misclassification. We expect that this will not be related to exposure to air pollution and nondifferential misclassification should bias the results to the null.

Conclusion

This study demonstrates that, on an additive scale, air pollution components pose a risk to human health, particularly among the very elderly population in the United States. The increase in the probability of hospital admissions with cardiovascular and respiratory outcomes seems to be most pronounced at lower exposure concentrations for all pollutants. Given that more than half of the US population is exposed to such levels, this issue should be of great concern to clinicians and policymakers alike.

ARTICLE INFORMATION

Received July 15, 2020; accepted December 14, 2020.

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Sources of Funding

This study was supported by the National Institutes of Health/National Institute of Environmental Health Sciences (grants P30 ES000002 and R01 ES024332) and US Environmental Protection Agency (grant RD-83587201). Its contents are solely the responsibility of the grantee and do not necessarily represent the official views of the US Environmental Protection Agency. Furthermore, the US Environmental Protection Agency does not endorse the purchase of any commercial products or services mentioned in the publication.

Disclosures

Dr Schwartz has appeared as an expert witness on behalf of the US Department of Justice in cases involving violations of the Clean Air Act. The other authors report no conflicts.

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ATTACHMENT B

United States Government Accountability Office

Report to Congressional Requesters

November 2020

AIR POLLUTION

Opportunities to Better Sustain and Modernize the National Air Quality Monitoring System

GAO-21-38

GAO Highlights

Highlights of GAO-21-38, a report to congressional requesters

November 2020

AIR POLLUTION

Opportunities to Better Sustain and Modernize the National Air Quality Monitoring System

Why GAO Did This Study

The national ambient air quality monitoring system shows that the United States has made progress in reducing air pollution but that risks to public health and the environment continue in certain locations. The system consists of sites that measure air pollution levels around fixed locations across the country using specific methods. Since the system began in the 1970s, air quality concerns have changed—such as increased concern about the health effects of air toxics.

GAO was asked to evaluate the national air quality monitoring system. This report examines the role of the system and how it is managed, challenges in managing the system and actions to address them, and needs for additional air quality information and actions to address challenges in meeting those needs.

GAO reviewed literature, laws, and agency documents; conducted a demonstration of low-cost sensors; and interviewed EPA officials, selected state and local officials, representatives from air quality associations, and stakeholders.

What GAO Recommends

GAO is making two recommendations for EPA to (1) establish an asset management framework for the monitoring system that includes key characteristics and (2) develop an air quality monitoring modernization plan that aligns with leading practices. In written comments on the report, EPA generally agreed with the recommendations.

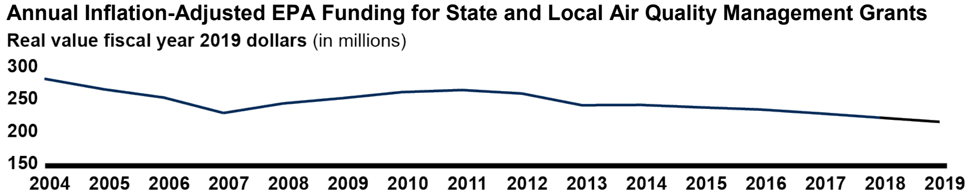
View GAO-21-38. For more information, contact J. Alfredo Gómez at (202) 512-3841 or gomezj@gao.gov.

What GAO Found

The ambient air quality monitoring system is a national asset that provides standardized information for implementing the Clean Air Act and protecting public health. The Environmental Protection Agency (EPA) and state and local agencies cooperatively manage the system, with each playing different roles in design, operation, oversight, and funding. For example, EPA establishes minimum requirements for the system, and state and local agencies operate the monitors and report data to EPA.

Officials from EPA and selected state and local agencies identified challenges related to sustaining the monitoring system. For example, they said that infrastructure is aging while annual EPA funding for state and local air quality management grants, which cover monitoring, has decreased by about 20 percent since 2004 after adjusting for inflation (see fig.). GAO found inconsistencies in how EPA regions have addressed these challenges. GAO's prior work has identified key characteristics of asset management, such as identifying needed resources and using quality data to manage infrastructure risks, which can help organizations optimize limited resources. By developing an asset management framework that includes such characteristics, EPA could better target limited resources toward the highest priorities for consistently sustaining the system.

Annual Inflation-Adjusted EPA Funding for State and Local Air Quality Management Grants



Source: GAO analysis of Environmental Protection Agency and U.S. Department of Commerce, Bureau of Economic Analysis, data. | GAO-21-38

Air quality managers, researchers, and the public need additional information so they can better understand and address the health risks from air pollution, according to GAO's review of literature and interviews GAO conducted. These needs include additional information on (1) air toxics to understand health risks in key locations such as near industrial facilities; and (2) how to use low-cost sensors to provide real-time, local-scale air quality information. EPA and state and local agencies face persistent challenges meeting such air quality information needs, including challenges in understanding the performance of low-cost sensors. GAO illustrated this challenge by collecting air quality data from low-cost sensors and finding variability in their performance. EPA has strategies aimed at better meeting the additional air quality information needs of managers, researchers, and the public, but the strategies are outdated and incomplete. For example, they do not clearly define roles for meeting additional information needs. GAO's prior work on asset management suggests that a more strategic approach could help EPA modernize the system to better meet the additional information needs. By developing a modernization plan that aligns with leading practices for strategic planning and risk management, such as establishing modernization goals and roles, EPA could better ensure that the system meets the additional information needs of air quality managers, researchers, and the public and is positioned to protect public health.

Contents

Tables

Figures

Abbreviations

AQI	Air Quality Index
CASTNET	Clean Air Status and Trends Network
COVID-19	Coronavirus Disease 2019
CSN	$PM_{2.5}$ Chemical Speciation Network
EPA	Environmental Protection Agency
IMPROVE	Interagency Monitoring of Protected Visual Environments
IRIS	Integrated Risk Information System
NAAQS	National Ambient Air Quality Standards
NADP	National Atmospheric Deposition Program
NASA	National Aeronautics and Space Administration
NATTS	National Air Toxics Trends Stations
NOAA	National Oceanic and Atmospheric Administration
PAMS	Photochemical Assessment Monitoring Stations
PFAS	per- and polyfluoroalkyl substances
$PM_{2.5}$	particulate matter less than or equal to 2.5 micrometers in diameter
PM_{10}	particulate matter less than or equal to 10 micrometers in diameter
SLAMS	State and Local Air Monitoring Stations

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November 12, 2020

The Honorable Thomas Carper
Ranking Member
Committee on Environment and Public Works
United States Senate

The Honorable Sheldon Whitehouse
Ranking Member
Subcommittee on Clean Air and Nuclear Safety
Committee on Environment and Public Works
United States Senate

The Honorable Susan Collins
United States Senate

Data from the national ambient air quality monitoring system show that the United States has made significant progress in reducing air pollution levels since the 1970s but that air pollution continues to harm public health and the environment in certain locations.[1] The monitoring system consists of sites that measure air pollution levels around fixed locations across the country using methods and quality assurance procedures approved by the Environmental Protection Agency (EPA). Air quality managers, researchers, and the public use data from the national ambient air quality monitoring system to characterize levels of pollution, study the human health and ecological effects of air pollution, develop strategies to reduce adverse health effects, and demonstrate progress in addressing air quality issues over time.

EPA oversees the national ambient air quality monitoring system, and state, local, and tribal air monitoring agencies generally own the equipment at the sites within the monitoring system.[2] In fiscal year 2020,

[1]"Ambient air" means that portion of the atmosphere, external to buildings, to which the general public has access. 40 C.F.R. § 50.1(e).

[2]The scope of this report does not include air quality monitoring on tribal lands. A 1998 EPA rule specifies the Clean Air Act provisions for which it is appropriate to treat Indian tribes in the same manner as states, establishes the requirements that Indian tribes must meet if they choose to seek such treatment, and provides for awards of federal financial assistance to tribes to address air quality problems. 63 Fed. Reg. 7254 (Feb. 12, 1998). We have ongoing work related to EPA grants for tribes and have identified air quality management on tribal lands as an area for potential future work. See app. I for additional information on this and other potential future oversight work related to air quality issues.

EPA provided about $225 million for air quality management programs that included ambient air monitoring, according to EPA data. By comparison, the nation's ambient air quality monitoring system informs regulatory and compliance decisions that have associated costs and benefits totaling billions of dollars, including the costs of strategies for reducing air pollution and the benefits associated with reducing adverse health and ecological effects from poor air quality.

Air quality concerns have changed since the national ambient air quality monitoring system was established by amendments to the Clean Air Act in the 1970s.[3] For example, concerns have emerged about issues such as the health effects of air toxics; the localized effects of currently unregulated pollutants; and the international transport of pollutants from regions with emerging economies, such as East Asia. Finally, technologies for measuring air quality monitoring—including sensors and satellites—have improved since the inception of the nation's air quality monitoring system, providing opportunities to enhance information on air quality.

You asked us to evaluate the national ambient air quality monitoring system. This report examines (1) the role that the national ambient air quality monitoring system plays in managing air quality and how EPA and state and local agencies manage the system; (2) the challenges that EPA and selected state and local agencies face in managing the national ambient air quality monitoring system and the extent to which EPA has addressed and could better address these challenges; (3) what additional air quality monitoring information could help meet the needs of air quality managers, researchers, and the public; and (4) the challenges EPA and selected state and local agencies face in meeting air quality information needs and the extent to which EPA has addressed and could better address these challenges.

To address our objectives, we reviewed relevant documents and literature. Specifically, we identified and reviewed federal laws and regulations governing the national ambient air quality monitoring system; EPA reports, guidance, and information on the oversight and operation of the monitoring system; and 10 studies and articles, identified in a

[3]42 U.S.C. §7401 et seq. The Clean Air Act was also significantly amended in 1977 and 1990.

literature review, which discussed the performance of the monitoring system or emerging air pollution issues.

We also conducted a series of interviews with knowledgeable federal, state, and local officials and representatives from air quality associations.[4] We interviewed knowledgeable EPA officials from the Office of Air Quality Planning and Standards within the Office of Air and Radiation; the Office of Research and Development; and six regional offices. We selected EPA regional offices in areas across the country with different characteristics that might be associated with a range of monitoring needs and considerations, such as different air quality concerns and population densities. We also conducted semistructured interviews with officials from 14 state and local air quality monitoring agencies within the selected EPA regions.[5] We selected state and local agencies to include jurisdictions with a range of characteristics potentially affecting the design and operation of their air quality monitoring networks, such as different air quality issues, population densities, and approaches to air toxics monitoring. Our findings from these interviews cannot be generalized to other EPA regions, states, or localities we did not include in our review. Finally, we interviewed representatives from the two national and six regional associations of state and local air quality agencies that represent state and local areas across the country.

In addition, we used other methodologies to address specific objectives. To examine the extent to which EPA could better address challenges in managing the monitoring system and meeting air quality information needs, we also reviewed our past work on asset management, strategic planning, and risk management. To identify what additional air quality monitoring information could help meet the needs of air quality managers, researchers, and the public, we also interviewed 10 knowledgeable

[4]To identify the number of interviewees who expressed particular views, we use the following modifiers throughout the report: “some” represents two to four interviewees, “several” represents five to eight interviewees, and “many” represents nine or more interviewees. We considered officials from a state or local agency or representatives from a national or regional association to be one interviewee, even though multiple officials or representatives may have participated in the interview.

[5]Tribal governments also partner with EPA to manage monitoring sites that are located on tribal lands. According to the National Tribal Air Association, which was founded in 2002 through an EPA grant, 88 tribes operated air monitors in 2020. The scope of this report does not include tribes’ management of air quality monitoring programs, and we did not interview tribal air quality agencies for this report. We have ongoing work related to EPA grants for tribes and have identified air quality management on tribal lands as an area for potential future work (see app. I).

stakeholders, selected based on their experience using air quality information and their knowledge about the extent to which the monitoring system produces needed air quality information. These stakeholders included representatives of organizations focused on the health effects of air pollution; academic faculty; and individuals from the private sector who could discuss modern technologies for measuring air quality, including low-cost sensor technologies. Our findings from these interviews cannot be generalized to other stakeholders we did not interview. Finally, to help identify challenges in meeting air quality information needs, we also conducted our own demonstration of sensor technologies by purchasing five low-cost air quality sensors and deploying them outside of the GAO building in Washington, D.C. For additional details on our scope and methodology, see appendix II.

We conducted this performance audit from March 2018 to November 2020 in accordance with generally accepted government auditing standards. Those standards require that we plan and perform the audit to obtain sufficient, appropriate evidence to provide a reasonable basis for our findings and conclusions based on our audit objectives. We believe that the evidence obtained provides a reasonable basis for our findings and conclusions based on our audit objectives.

Background

This section describes the categories of air pollutants regulated under the Clean Air Act and national air quality trends and issues.

Air Pollutants Defined by the Clean Air Act

The Clean Air Act provides the framework for protecting air quality in the United States.[6] Under the Clean Air Act, EPA sets different types of limits—ambient air standards and emissions standards—for two categories of air pollutants.

The first category—the “criteria” pollutants for which EPA has established standards for the allowable levels of each pollutant in the ambient air—includes carbon monoxide, lead, ozone, particulate matter, nitrogen

[6]The purposes of the Clean Air Act are to, among other things, to protect and enhance the quality of the nation’s air resources so as to promote the public health and welfare and the productive capacity of its population. 42 U.S.C. § 7401(b)(1).

dioxide, and sulfur dioxide.[7] EPA sets these allowable standards—called the National Ambient Air Quality Standards (NAAQS)—at levels intended to protect public health, including the health of susceptible and vulnerable populations such as people with asthma, children, and elderly people.[8] Using information collected by the national ambient air quality monitoring system, EPA classifies a geographic area that does not meet the NAAQS for a criteria pollutant as a "nonattainment" area. When an area is in nonattainment, the Clean Air Act requires that the relevant air quality management agency develop plans to reduce air pollution to help bring the area into attainment.

The criteria pollutants are commonly found throughout the United States and can harm public health, harm the environment, and cause property damage. Some criteria pollutants, such as sulfur dioxide, nitrogen dioxide, carbon monoxide, and lead, can be directly emitted from sources such as power plants, factories, and motor vehicles. Particulate matter can be emitted directly from a source, such as a construction site, smokestack, or fire, or formed in the atmosphere from the combination of so-called "precursor" chemicals such nitrogen dioxide and sulfur dioxide. Ozone forms in the atmosphere from the combination of precursors emitted from sources such as motor vehicles and refineries in the presence of sunlight.[9]

The second category of pollutants currently includes 187 pollutants listed under the 1990 Clean Air Act Amendments and subsequent EPA

[7]EPA calls these "criteria" air pollutants because EPA sets the standards based on health-based criteria, which are characterizations of the latest scientific information regarding their effects on health or welfare. EPA has established standards for two different sizes of particulate matter: particulate matter less than or equal to 10 micrometers in diameter, known as PM_{10}, and particulate matter less than or equal to 2.5 micrometers in diameter, known as $PM_{2.5}$.

[8]In addition, EPA sets "secondary standards" to protect the public welfare from any known or anticipated adverse effects associated with the presence of such air pollutant in the ambient air.

[9]Ozone precursors include oxides of nitrogen, which are emitted from sources including automobiles and power plants, and volatile organic compounds, which are emitted from sources including refineries and chemical plants. Both $PM_{2.5}$ and ozone are referred to as secondary pollutants because they are formed as a result of atmospheric reactions.

regulations as “hazardous air pollutants.”[10] EPA also refers to these pollutants as “air toxics.”[11] For air toxics, EPA has not established ambient air standards but regulates them by establishing standards that limit the amount of emissions allowed from individual pollution sources. The 1990 Clean Air Act amendments required EPA to identify categories of industrial sources for the listed air toxics and require the sources to take such measures as installing emissions controls or changing production processes to meet the emissions standards. The 1990 amendments also require EPA to evaluate the remaining health risks in each source category once emissions limits are met, to determine whether the standards sufficiently protect public health.

Air toxics are pollutants known to cause or suspected of causing cancer, birth defects, reproduction problems, and other serious illnesses. Air toxics include pollutants such as benzene, found in gasoline, and methylene chloride, which a number of industries use as a solvent and paint stripper.[12] The health risks of air toxics can vary considerably. Therefore, small quantities of more harmful pollutants can pose greater health risks than large quantities of less harmful pollutants. Air toxics can originate from stationary sources such as factories, refineries, and power plants; mobile sources such as cars, trucks, and buses; and indoor sources such as some building materials and cleaning solvents.

National Air Quality Trends and Issues

For criteria pollutants, since the passage of the Clean Air Act in 1970, data reported by the national ambient air quality monitoring system has shown improvements in the nation’s air quality. In its 2020 report on national air quality trends, EPA reported that nationally, criteria air

[10]For a list of these pollutants, see EPA, *Initial List of Hazardous Air Pollutants with Modifications*, accessed August 6, 2020. https://www.epa.gov/haps/initial-list-hazardous-air-pollutants-modifications. On June 18, 2020, EPA published a notice in the *Federal Register* granting petitions to add one additional air toxic—1-bromopropane, a solvent used in electronics and metal cleaning, surface coatings, and dry cleaning—to the list of regulated hazardous air pollutants. Next, EPA will take a separate regulatory action to add 1-bromopropane to the list, increasing the total number of listed air toxics to 188.

[11]EPA uses the term “hazardous air pollutants” for air toxics that are specifically listed as relevant to programs in the Clean Air Act. Some air toxics are not included on the list of hazardous air pollutants.

[12]Some air toxics are also precursors to ozone formation. In addition, lead compounds are air toxics, while lead is a criteria pollutant.

pollutant levels have dropped significantly since 1990.[13] For example, according to the 2020 report, national averages of carbon monoxide and sulfur dioxide have declined by 78 and 90 percent, respectively, since 1990.[14] Cleaner-burning cars and trucks have led to the declines in carbon monoxide levels, while reductions in emissions from coal-fired power plants have contributed to declines in sulfur dioxide levels.

Even though the levels of criteria pollutants have declined nationally in the past few decades, EPA reported in 2020 that some pollutants continue to pose serious air quality problems in areas of the United States. For example, many areas of the country remain out of attainment of the NAAQS for ozone (fig. 1 shows ozone nonattainment areas).[15] According to an EPA report based on 2010 population data, approximately 130 million people in the United States live in a nonattainment area for at least one of the criteria pollutants, which amounts to around 40 percent of the U.S. population.[16]

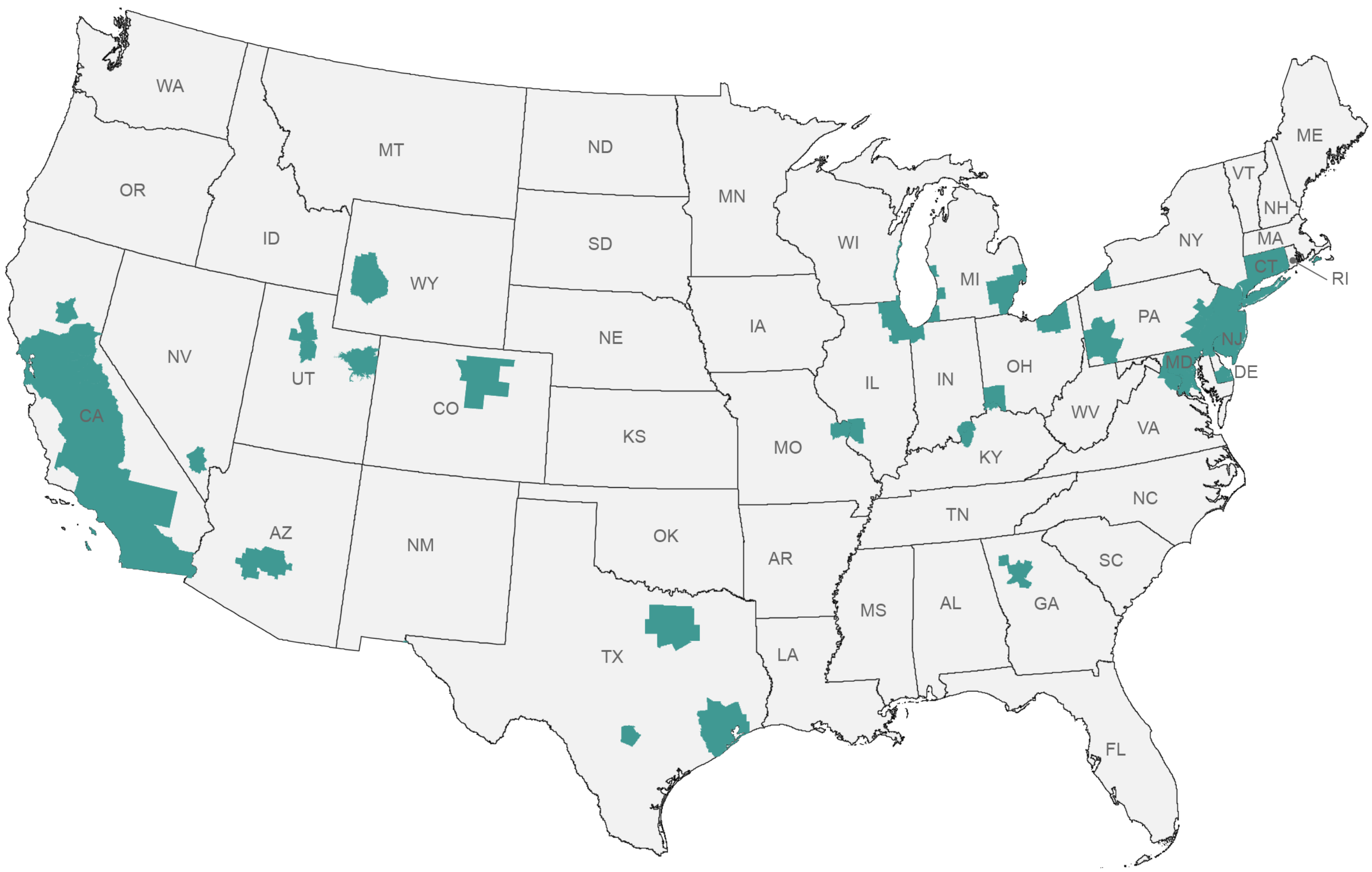
[13]EPA, *Our Nation's Air,* accessed September 10, 2020. https://www.epa.gov/air-trends.

[14]Measured as 8-hour averages of carbon monoxide and 1-hour averages of sulfur dioxide.

[15]In addition, some areas of the country remain in nonattainment of the NAAQS for particulate matter less than or equal to 2.5 micrometers in diameter ($PM_{2.5}$), sulfur dioxide, lead, and particulate matter less than or equal to 10 micrometers in diameter (PM_{10}). Since 2010, there have been no areas in nonattainment of the NAAQS for carbon monoxide or nitrogen dioxide. A particle 2.5 micrometers in diameter is about 30 times smaller than the diameter of an average human hair.

[16]This information was current as of June 30, 2020. EPA, *Summary Nonattainment Area Population Exposure Report*, accessed July 31, 2020. https://www3.epa.gov/airquality/greenbook/popexp.html.

Figure 1: Nonattainment Areas for the Ozone National Ambient Air Quality Standards (NAAQS)



Source: GAO analysis of Environmental Protection Agency (EPA) data. | GAO-21-38

Note: The map shows areas in nonattainment based on EPA data as of September 2, 2020. The areas shown on the map were designated as nonattainment areas for either the 2008 ozone NAAQS (75 parts per billion (ppb), averaged over 8 hours) or the 2015 ozone NAAQS (70 ppb, averaged over 8 hours). EPA estimates that, based on 2010 population data, approximately 122 million people live in an area in nonattainment of the 2015 ozone NAAQS.

For air toxics, EPA's 2014 *National Air Toxics Assessment* found that, nationwide, total emissions of air toxics were declining and that available monitoring data showed average levels of some air toxics trending downward.[17] However, pollution from air toxics has raised public health

[17]EPA, *2014 National Air Toxics Assessment*, accessed April 9, 2020. https://www.epa.gov/national-air-toxics-assessment/2014-national-air-toxics-assessment. The *2014 National Air Toxics Assessment* was released in August 2018. The assessment uses air toxics emissions data from 2014.

concerns about air quality in communities across the country, and the 2014 National Air Toxics Assessment identified many communities facing elevated health risks from air toxics. The pollutants driving risks across the country included benzene, ethylene oxide, and formaldehyde, which are used or produced in industrial facilities such as oil and gas wells, medical sterilization facilities, and incinerators.

The Air Quality Monitoring System Is a National Asset That Provides Information for Protecting Public Health and Is Cooperatively Managed by EPA and State and Local Agencies

The national ambient air quality monitoring system is a national asset that provides standardized information across the country that is essential for Clean Air Act compliance and other efforts to manage public health risks. EPA and state and local agencies cooperatively manage the monitoring system and play different roles in its design, operation, oversight, and funding.

The Air Quality Monitoring System Is a National Asset That Provides Standardized Information for Implementing the Clean Air Act and Understanding Public Health Risks

The ambient air quality monitoring system is a national asset, according to literature we reviewed, stakeholders, and officials from EPA and selected state and local agencies. It provides value to the nation by (1) producing standardized information across the country through a suite of networks and (2) supporting Clean Air Act implementation and the understanding of public health risks from air pollution.[18]

[18]While not specifically defined as such, the monitoring system has characteristics of critical infrastructure, including that it is essential in the protection of national public health. The Department of Homeland Security's *2013 National Infrastructure Protection Plan* defines critical infrastructure as those assets, systems, and networks that underpin American society. Department of Homeland Security, *National Infrastructure Protection Plan 2013: Partnering for Critical Infrastructure Security and Resilience* (Washington, D.C.: 2013).

The Monitoring System Provides Standardized Air Quality Information across the Country through a Suite of Networks

The ambient air quality monitoring system provides standardized information across the country through a suite of networks focused on different air quality issues. The networks have common methods for producing data at their monitoring sites, allowing the comparison of data across the country to provide a national perspective of various air quality issues.[19] Table 1 describes the networks within the national ambient air quality monitoring system: (1) required State and Local Air Monitoring Stations (SLAMS) networks, which measure levels of the criteria pollutants and the precursor pollutants that mix to form criteria pollutants; (2) voluntary networks designed to measure air toxics, including a national network for establishing trends in air toxics and state and local networks designed to target specific concerns about air toxics; and (3) specialized networks focused on certain pollution issues, such as visibility and deposition of pollutants from the atmosphere into ecosystems.

[19]Certain state and local air toxics monitoring programs use common methods for producing data. However, since these are not required networks, the use of common methods across all state and local air toxics monitoring is not assured.

Table 1: National Ambient Air Quality Monitoring System

Network	Purpose	Start year	No. of sites[a]
State and Local Air Monitoring Stations (SLAMS) network			
Criteria pollutant networks	Provide air pollution data to the general public in a timely manner; support compliance with the National Ambient Air Quality Standards (NAAQS) and emissions strategy development, and support air pollution research studies.	1980	4,300+
Photochemical Assessment Monitoring Stations (PAMS)	Measure ozone precursors to better characterize the nature and extent of ozone problems in nonattainment areas.	1994	69
$PM_{2.5}$ Chemical Speciation Network (CSN)	Provide data on the chemical composition of particulate matter less than or equal to 2.5 micrometers in diameter ($PM_{2.5}$) to assess trends, develop emissions control strategies, and support health studies, among other things.	2002	154
Near-Road NO_2 Network	Measure nitrogen dioxide (NO_2) and other pollutants near roads in larger urban areas where peak hourly levels are expected to occur.	2010	74
National Core (NCore) network	Support air quality model evaluations, long-term health assessments, compliance through comparison to the NAAQS, and ecosystem assessments.	2011	78
Networks for assessing air toxics			
National Air Toxics Trends Stations (NATTS) network	Identify trends in air toxics levels to assess progress toward emission reduction goals, evaluate public exposure, and characterize risk.	2003	24
State and local air toxics monitoring	Support state and local air toxics programs and identify geographic areas at high risk.	1985	240+
Specialized networks			
Interagency Monitoring of Protected Visual Environments (IMPROVE)	Establish current visibility conditions in visibility-protected federal areas, identify emissions sources, document trends, and provide regional haze monitoring.	1985	110
Clean Air Status and Trends Network (CASTNET)	Assess environmental results of emissions reductions programs, such as a program to reduce acid rain, and pollutant impacts to sensitive ecosystems and vegetation.	1991	96
National Atmospheric Deposition Program (NADP)	Provide data on the amounts, trends, and geographic distributions of ammonia, mercury, and other pollutants found in precipitation that can affect the environment.	1978	473

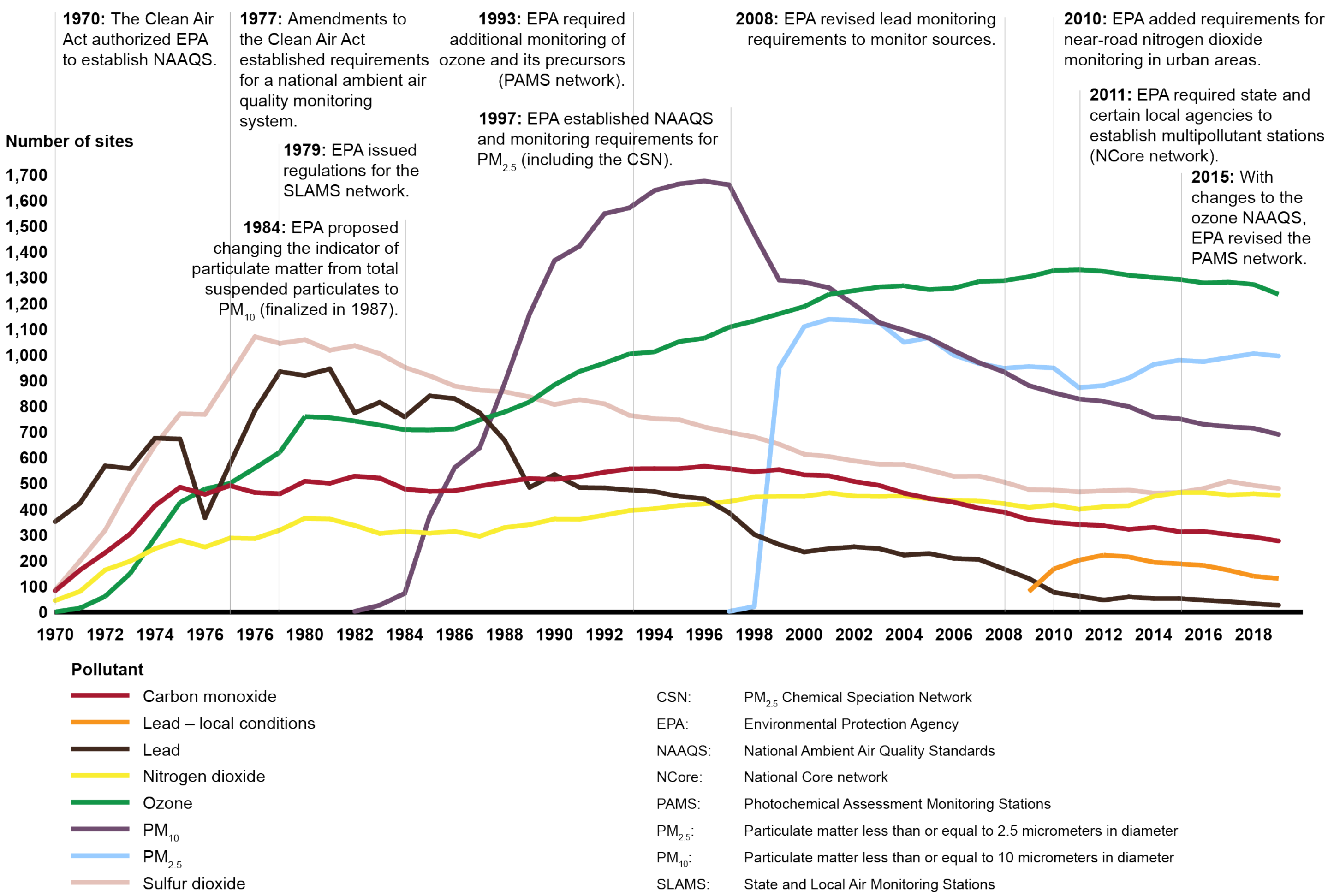
Source: GAO analysis of Environmental Protection Agency information. | GAO-21-38

[a]These numbers include sites on tribal lands that report data to the Environmental Protection Agency.

As shown in table 1, the vast majority of sites within the monitoring system are associated with the SLAMS networks and provide standardized information on criteria pollutants. These networks are required by EPA regulations and have evolved over time in response to regulatory changes under the Clean Air Act, including revisions to the NAAQS (see fig. 2), according to EPA officials.[20] In some cases, these regulatory changes resulted in the development of new networks designed to address a particular air quality issue. For example, EPA has issued regulations requiring the establishment of the Photochemical Assessment Monitoring Stations (PAMS) network to obtain more comprehensive data on ozone pollution, including additional information on ozone precursors. In 2015, as a result of revisions to the ozone NAAQS, EPA revised the PAMS network to expand its geographic coverage.

[20]The Clean Air Act requires that EPA review NAAQS every 5 years and revise them if the review deems that a change is warranted. According to EPA officials, during these reviews, EPA also reviews the associated air quality monitoring networks and methods.

Figure 2: Number of Sites Monitoring Criteria Pollutants and Key EPA Actions Driving Changes

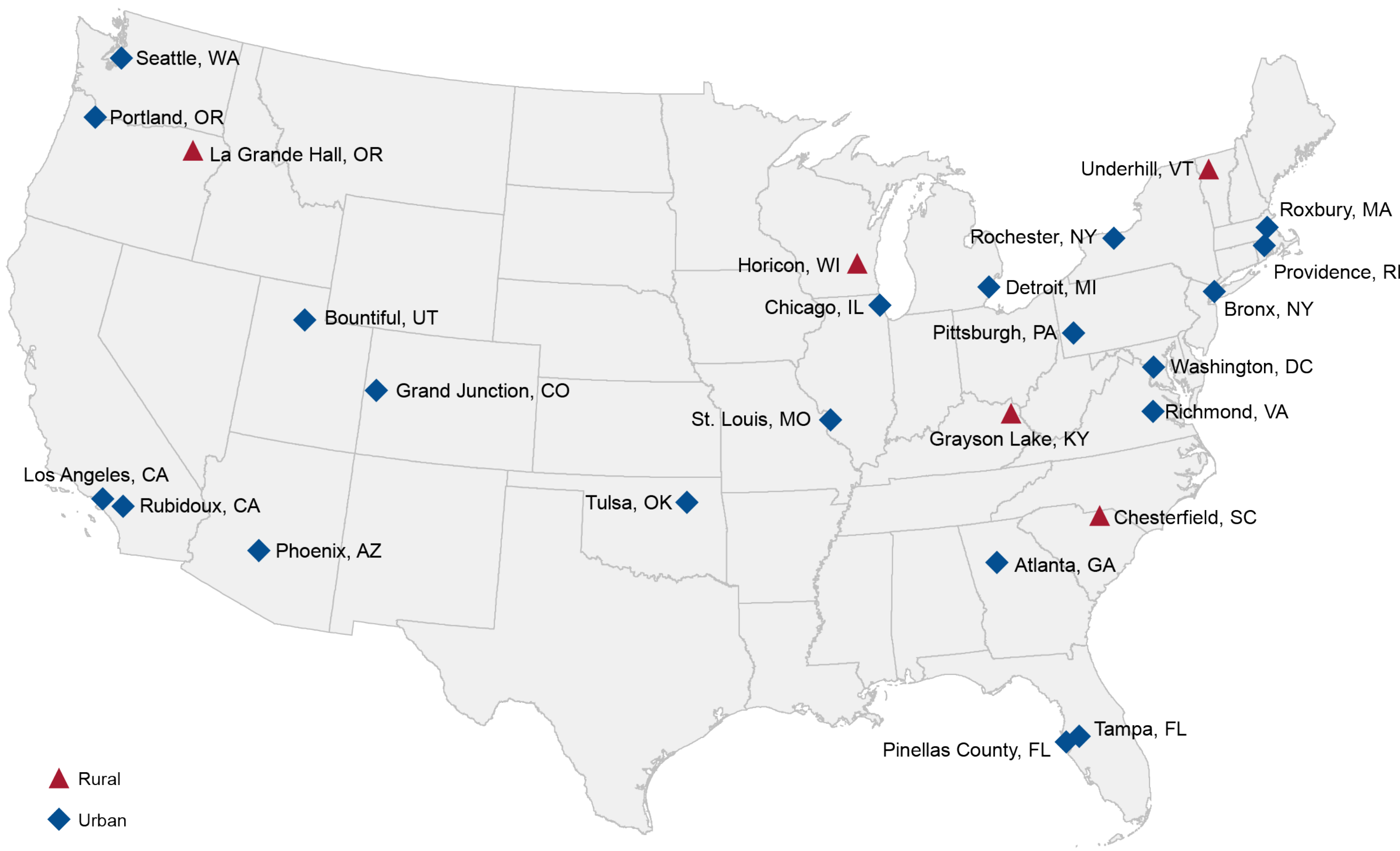


Source: GAO analysis. | GAO-21-38

Note: One monitoring site may monitor multiple pollutants.

For air toxics, EPA established the National Air Toxics Trends Stations (NATTS) network in 2003 to provide information of consistent quality on trends of certain air toxics in a limited number of locations across the country. The NATTS network began with 13 sites and grew to a maximum of 27 sites in 2008. The network currently includes 26 sites at urban and rural locations (see fig. 3). At a minimum, EPA asks that each NATTS site monitor 19 air toxics, including some widespread air toxics that present potential health concerns across the country, to develop information on trends.[21] Typically, though, NATTS sites monitor over 100 air toxics.

Figure 3: Location of National Air Toxics Trends Stations



Source: GAO analysis of Environmental Protection Agency data.. | GAO-21-38

[21]Specifically, at a minimum, each NATTS site monitors acrolein, benzene, 1,3-butadiene, carbon tetrachloride, chloroform, perchloroethylene, trichloroethylene, vinyl chloride, acetaldehyde, formaldehyde, benzo(a)pyrene, naphthalene, arsenic compounds, beryllium compounds, cadmium compounds, lead compounds, manganese compounds, nickel compounds, and ethylene oxide.

Finally, the national ambient air monitoring system includes specialized networks designed to provide consistent information across the country on pollution issues in certain environments or ecosystems.[22] For example, these networks monitor pollution that impairs visibility in some national parks and wilderness areas or monitors air pollutants, such as mercury, that can affect ecosystems and water quality.[23] While these specialized networks are a part of the national ambient air monitoring system, the remainder of this report does not focus on them because their sites are managed through different mechanisms than the criteria pollutant and air toxics networks.[24]

The Monitoring System Provides Information Essential for Implementing the Clean Air Act and Understanding Public Health Risks

The national ambient air quality monitoring system provides information essential for assessing Clean Air Act compliance, according to some literature we reviewed and EPA and state and local agency officials we interviewed. EPA's policy is to assure uniform enforcement of the Clean Air Act across the country, and the monitoring system plays a key role in this by providing data for comparison with the NAAQS to determine whether an area is in attainment.[25] When an area does not attain the NAAQS, the monitoring system provides key measurements to evaluate strategies for cleaning up the air and to track progress toward NAAQS attainment.

In addition to supporting Clean Air Act compliance, the national ambient air quality monitoring system provides information critical to help air quality managers, researchers, and the public to understand and manage health risks from air pollution, according to some literature we reviewed and stakeholders we interviewed. For example, information from criteria pollutant networks forms much of the basis for studies on the health

[22]As shown in table 1, these specialized networks include the Interagency Monitoring of Protected Visual Environments (IMPROVE) network, the Clean Air Status and Trends Network (CASTNET), and the National Atmospheric Deposition Network (NADP).

[23]See app. I for potential additional work related to air quality impacts on ecosystems, which would involve some of these networks.

[24]IMPROVE is managed by a steering committee of representatives from six federal agencies, four air quality organizations, and three associate members—the Arizona Department of Environmental Quality, Environment Canada, and the South Korea Ministry of Environment. CASTNET is managed by EPA; the National Park Service; the Bureau of Land Management; and other federal, state, local, and tribal partners. NADP is managed by federal, state, tribal, and local government organizations; educational institutions; and nongovernmental agencies and institutions.

[25]EPA policy is to assure "fair and uniform application" by all regions of EPA criteria for enforcing the Clean Air Act. 40 C.F.R. § 56.3(a).

effects of criteria pollutants that EPA uses to determine whether new information warrants changes to the NAAQS to adequately protect public health. In addition, information from NATTS and state and local air toxics monitoring networks helps to identify air toxics trends, characterize local air toxics problems, and track progress of air toxics reduction activities.

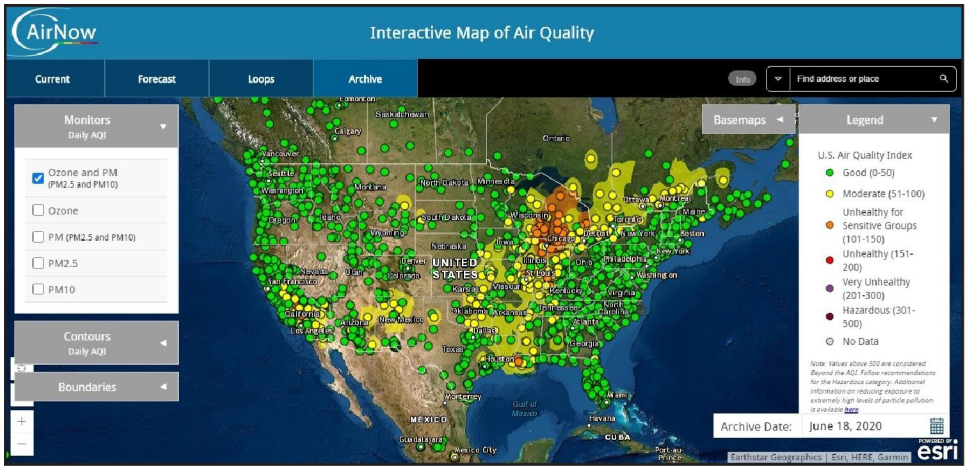
The monitoring system also provides reliable, “gold standard” information that scientists and others can use to validate air quality measurements for research or test new air quality measurement technologies that further the understanding of health risks from air pollution, according to some stakeholders. One stakeholder we interviewed had created detailed maps of $PM_{2.5}$ levels in the air for a region by calibrating satellite data with $PM_{2.5}$ data that the monitoring system collected. Another stakeholder we interviewed used monitoring system data to calibrate sensors worn by individuals to measure their personal exposure to air pollution.

Finally, the national ambient air quality monitoring system provides some near real-time air quality information for ozone and particulate matter, which organizations and individuals can use to evaluate daily health risks and change behaviors accordingly. EPA reports near real-time air quality information from the monitoring system for locations across the United States on its AirNow website using an Air Quality Index (AQI) (see fig. 4 for an example).[26] EPA calculates the AirNow AQI based on monitoring data for ozone and particulate matter and reports it in color-coded categories based on the levels of health concern posed by the amount of air pollution over certain time periods.[27]

[26]See www.airnow.gov.

[27]The categories include good, moderate, unhealthy for sensitive groups, unhealthy, very unhealthy, and hazardous.

Figure 4: Near Real-time Air Quality Information from AirNow.gov



AirNow showing national air quality, June 18, 2020.

AirNow showing the impact of wildfires on national air quality, September 18, 2020.

Source: Environmental Protection Agency (AirNow.gov). | GAO-21-38

EPA and State and Local Agencies Cooperatively Manage the National Air Quality Monitoring System

EPA and state and local agencies cooperatively manage the national ambient air quality monitoring system. The agencies play different roles in managing the system. Specifically, (1) EPA establishes requirements for the design of the monitoring system; (2) state and local agencies design and operate the networks within the monitoring system; (3) EPA coordinates with state and local agencies on monitoring system oversight, technical assistance, and data management; and (4) EPA and state and local governments provide funding for the monitoring system.

EPA Establishes Requirements for the Design of the Monitoring System

EPA's Office of Air Quality Planning and Standards—the office charged with preserving and improving air quality in the United States—establishes requirements for the design of the national ambient air quality monitoring system. For the required SLAMS networks measuring criteria pollutants, EPA issues regulations to establish the minimum design criteria, which include requirements for what pollutants to measure, how many monitoring sites a network needs, and where to locate sites.[28]

EPA has established different minimum monitoring requirements for criteria pollutants based on factors such as population, pollutant levels, and emissions. The requirements for ozone, $PM_{2.5}$, and PM_{10} are based, in part, on a combination of pollution levels and population. For these criteria pollutants, EPA requires that state and local agencies operate a minimum number of monitors based on an area's population and on pollution levels relative to the NAAQS. As an example, for ozone, EPA requires that a state or locality have at least three monitors for a metropolitan area with a combined population between 4 million and 10 million and ozone levels close to or above the NAAQS. By contrast, EPA requires a minimum of one ozone monitor for another metropolitan area of the same size, but with ozone levels significantly below the NAAQS. For other criteria pollutants, the minimum number of monitors required depends primarily on population for nitrogen dioxide, emissions for lead, and both population and emissions for sulfur dioxide.

In addition to minimum criteria for the number of monitors for specific pollutants, EPA has requirements for different types of monitoring sites for each criteria pollutant that state and local agencies must include within their networks. According to EPA documents, these site types are designed to ensure that a state or local agency's network covers specific factors, including (1) the maximum pollutant levels expected to occur in the area covered by the network; (2) typical pollutant levels in areas of high population density; (3) the impact of significant air pollution sources on air quality; (4) background pollution levels and the extent of regional pollutant transport among populated areas; and (5) the impacts of air pollution on visibility or other welfare-based impacts, such as vegetation damage.

Finally, EPA establishes the acceptable technologies and methods for measuring air pollution at monitoring sites to ensure that air quality

[28]40 C.F.R. Part 58, Appendix D, establishes network design criteria for ambient air quality monitoring of criteria pollutants. Appendix D notes that, in some cases, additional monitors beyond those minimally required may be needed to meet monitoring objectives.

monitoring data collected at different sites are gathered in a consistent manner and are reliable. EPA's Office of Research and Development manages research programs to assess, develop, and validate these methods. For measuring criteria pollutants for comparison to the NAAQS, EPA approves specific methods for sampling and analyzing the ambient air for a pollutant and designates them as "federal reference methods" or "federal equivalent methods."[29] For measuring air toxics, EPA develops approved methods for various classes of air toxics.

State and Local Agencies Design and Operate the Networks within the Monitoring System

The national monitoring networks each consist of individual state and local monitoring networks. A state or locality's network may include a combination of SLAMS sites, NATTS sites, and state and local air toxics sites.[30] State and local agencies manage their air quality monitoring networks by performing several functions, including (1) designing, establishing, and modifying the networks; (2) purchasing and maintaining monitoring infrastructure; and (3) operating monitoring sites and implementing quality assurance programs.

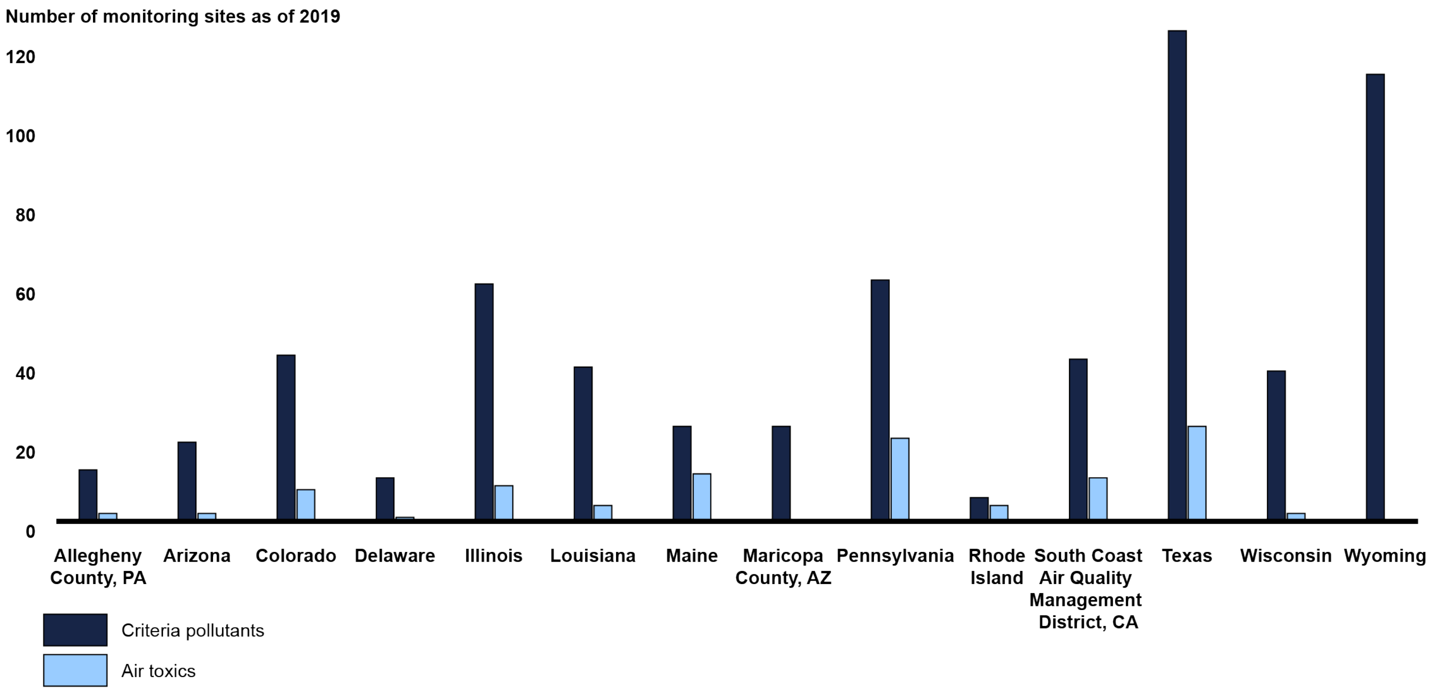
- **Designing, establishing, and modifying the monitoring networks.** State and local agencies design and establish monitoring networks within their jurisdictions. State and local networks vary significantly in terms of size and scope. Of the networks owned by our selected state and local agencies, the size and scope of the networks varied, along with differences in geographic scale, population, air quality issues, and available resources. As shown in figure 5, the networks of the 14 selected state and local agencies ranged from 10 monitoring sites in the small state of Rhode Island to 148 monitoring sites in the large state of Texas, and they varied significantly in terms of the number of sites monitoring air toxics.[31]

[29]EPA designates these methods under 40 C.F.R. Part 53.

[30]State and local agencies may also operate special purpose monitoring sites to fulfill very specific or short-term monitoring goals.

[31]These numbers are based on the number of sites that provide data to EPA and do not include some voluntary toxics monitoring. For example, according to its website, the Texas Council on Environmental Quality receives air toxics data from approximately 100 monitoring sites across Texas, mostly in urban and industrial areas.

Figure 5: Numbers of Monitoring Sites for Criteria Pollutants and Air Toxics in the Networks of Selected State and Local Air Quality Monitoring Agencies



Source: GAO analysis of information provided by state and local agencies. | GAO-21-38

Note: The data in the figure are based on the number of sites that provide data to the Environmental Protection Agency (EPA) and do not include some voluntary toxics monitoring that is not reported to EPA. Of the 113 criteria pollutant sites in Wyoming, 70 sites are associated with Wyoming's program to monitor particulate matter less than or equal to 10 micrometers in diameter (PM_{10}) at specific industrial sites—including in the Powder River Basin—as a part of their operating permits.

Per EPA requirements, state and local agencies develop annual network plans to demonstrate that their monitoring networks meet monitoring objectives and requirements, including minimum design criteria. In these plans, state and local agencies document proposed changes to their monitoring network design, such as new or discontinued sites, and identify plans for meeting any new EPA monitoring requirements, among other things. State and local agencies must make the plans publicly available and submit the plans to the applicable EPA regional office.

- **Purchasing and maintaining monitoring infrastructure.** State and local agencies purchase and maintain the monitoring infrastructure within their networks. Infrastructure within the national ambient air quality monitoring system includes monitoring sites and the associated equipment. A monitoring site typically consists of a shelter that houses and protects the monitoring equipment. The equipment at a site varies, depending on the pollutants that are monitored at the site, but may include sample collection devices such as filter holder assemblies for particulate matter or canisters for air toxics, equipment that analyzes air samples using EPA-approved technologies, calibration equipment, data loggers, computer systems, and heating and air conditioning systems. Figure 6 shows examples of monitoring equipment at some of the monitoring sites we visited.

Figure 6: Examples of Air Monitoring Sites and Monitoring Equipment

National Core network (NCore) monitoring site operated by the Wyoming Department of Environmental Quality

Near-road monitoring site operated by the Rhode Island Department of Environmental Management

Equipment for monitoring criteria pollutants operated by the Colorado Department of Public Health and Environment

Canisters used to collect samples for measuring air toxics operated by the Wisconsin Department of Natural Resources

Particulate matter monitoring site atop a building at the Illinois State Fairgrounds operated by the Illinois Environmental Protection Agency

Source: GAO. | GAO-21-38

State and local agencies make decisions about the type of equipment they will purchase, criteria for replacing equipment, and strategies for maintaining it. Some officials we interviewed from state and local agencies said they often try to purchase most of their equipment from one manufacturer to minimize the amount of training required for new equipment, and look to other agencies and EPA for guidance and information about different types of monitoring equipment.

- **Operating monitoring sites and implementing quality assurance programs.** State and local air quality agencies operate the monitoring sites within their networks. Among other functions, these agencies set up the monitoring sites, including installing equipment, electricity, and communications; develop and implement standard operating procedures; calibrate equipment; and maintain equipment and shelters. State and local agencies also establish and implement quality assurance programs to ensure that their monitoring programs function as intended and meet objectives for data quality.

EPA Coordinates with State and Local Agencies on Several Monitoring System Functions

EPA coordinates with state and local agencies on several functions, including monitoring system oversight, network assessment, technical assistance, and data management, with various EPA offices playing different roles. For example:

- **Oversight.** EPA's Office of Air Quality Planning and Standards establishes the quality assurance and oversight requirements for the monitoring system and develops and documents the programs and guidance for implementing these requirements. EPA's regional offices work directly with state and local agencies to evaluate compliance with the requirements through mechanisms that include (1) reviewing and approving state and local agencies' annual network plans to ensure that the networks comply with design requirements, and (2) conducting on-site reviews and inspections—called technical systems audits—of state and local agencies' monitoring programs every 3 years to assess compliance with the regulations governing the collection, analysis, validation, and reporting of air quality monitoring data.
- **Network assessment.** EPA requires that state and local agencies perform and submit to the EPA regional offices an assessment of their monitoring network every 5 years to determine whether it meets the regulatory monitoring objectives, whether new sites are needed or existing sites are no longer needed and can be terminated, and whether new technologies are appropriate for incorporation into the network. EPA regional offices review the 5-year network assessments to understand how the networks are performing, according to some EPA regional officials we interviewed.
- **Technical assistance.** EPA's Office of Air Quality Planning and Standards and EPA regional offices communicate with state and local agencies and provide information and technical assistance through

scheduled monthly calls hosted by EPA and quarterly calls hosted by national air quality associations, according to EPA officials. In addition, EPA hosts a biennial national air quality monitoring conference to provide training and presentations on various aspects of the monitoring system.[32] Finally, according to EPA officials, staff from EPA's regional offices regularly communicate with the state and local agencies within their regions to answer technical questions and provide support and guidance. Officials we interviewed from all of the 14 selected state and local agencies said their agencies had good working relationships with EPA.

- **Data management.** EPA's Office of Air Quality Planning and Standards and regional offices coordinate with state and local agencies to manage the data that the monitoring networks collect. State and local agencies are responsible for collecting, assessing, validating, and delivering air quality monitoring data to EPA. State and local agencies submit most monitoring data quarterly to EPA's Air Quality System—the centralized database for air quality data from the monitoring system. State and local agencies also transfer some monitoring data hourly to EPA's AirNow website, which reports near real-time air monitoring data. EPA's regional offices are responsible for assessing the quality of data from the state and local agencies within their regions, and EPA's Office of Air Quality Planning and Standards oversees and operates the Air Quality System and makes air quality information available to the public.

EPA and State and Local Governments Provide Funding for the Monitoring System

The national ambient air quality monitoring system relies on funding from federal, state, and local government sources. While EPA does not track all funding for monitoring, EPA officials estimated, based on their knowledge of state and local agency activities, that state and local agencies used between approximately $150 million and $170 million each year from federal, state, and local sources for air quality monitoring activities. EPA provides federal funding for the monitoring system through grants to state and local agencies under the Clean Air Act for a range of state and local air quality management activities, including air quality

[32]EPA has hosted this conference in conjunction with the National Association of Clean Air Agencies and the Association of Air Pollution Control Agencies. As a part of this work, we attended the 2018 National Ambient Air Monitoring Conference held in Portland, OR.

monitoring.[33] EPA regional offices administer and oversee the federal grants to state and local agencies. In fiscal year 2020, EPA allocated a total of approximately $225 million for air quality management grants using two different authorities, according to EPA data.[34]

First, Section 103 of the Clean Air Act authorizes EPA to award grants for specific air quality-related activities, including research, demonstrations, and training. In fiscal year 2020, EPA allocated approximately $50 million for Section 103 grants for activities including $PM_{2.5}$ monitoring, operation of NATTS sites, and Community Scale Air Toxics monitoring grants, according to EPA officials.[35] Section 103 does not require that state and local agencies provide matching amounts.

Next, under Section 105 of the Clean Air Act, EPA awards grants to state and local agencies for continuing air quality management activities, including developing and operating ambient air quality monitoring networks, developing and implementing air pollution emissions reduction measures, and implementing programs for improving visibility in national parks and wilderness areas. Grants that EPA awards under Section 105 may fund up to 60 percent of the cost of a state or local agency's air quality management program, and they require the state or local agency to provide matching funding for at least 40 percent of a program's cost. In fiscal year 2020, EPA allocated approximately $174 million for Section 105 grants, according to EPA data.

State and local air monitoring networks are also funded through state and local appropriations, revenue raised through fees and penalties, and other sources. According to a representative of the National Association of Clean Air Agencies, on average, state and local governments fund 75 percent of their overall air quality management programs, which include

[33]EPA provides guidance on the use of these grants for the ambient air quality monitoring system in its *National Program Manager Guidance – Monitoring Appendix* (see https://www.epa.gov/amtic/national-program-manager-npm-guidance-monitoring-appendix, accessed Oct. 30, 2020). According to EPA officials, this document offers direction and sets priorities for ambient air monitoring.

[34]According to EPA officials, this amount includes funding available for state, local, and tribal agencies. Of this total, EPA allocated approximately $12 million for tribal agencies in fiscal year 2020, according to the National Tribal Air Association.

[35]EPA periodically awards Community Scale Air Toxics Ambient Monitoring grants to help state, local, and tribal air agencies conduct air quality monitoring projects to address localized air toxics issues.

monitoring networks. However, the available sources of funding and the amount these sources provide varies among states and localities. Of the 14 state and local agencies we selected for interviews, 12 received monitoring funding from fees and penalties, five received monitoring funding from state or local appropriations, and four received monitoring funding from other sources such as state grants and industry-supported state funds. Among the 14 selected agencies, the portion of total monitoring costs covered by state or local funding ranged from zero for one agency—in other words, it was all federally funded—to approximately 90 percent for another agency.[36]

EPA and State and Local Agencies Face Challenges Related to Sustaining the Monitoring System, and EPA Has Opportunities to Address Them More Consistently

Officials from EPA and selected state and local agencies identified challenges in managing the national ambient air quality monitoring system related to sustaining the system. These challenges include declining funding and increasing demands on resources available for monitoring. EPA has initiated efforts that partially address these challenges, but its efforts have been inconsistent across regions. An asset management approach to managing the monitoring system could provide opportunities for EPA to address the challenges more consistently.

EPA and State and Local Agencies Face Declining Funding and Increasing Demands on Resources as Challenges Affecting Their Ability to Sustain the Monitoring System

Officials we interviewed from EPA and all of the selected state and local agencies and regional air quality associations said they faced challenges in managing the national ambient air monitoring system that affect their ability to sustain it. Primarily, federal funding for state and local monitoring programs has declined by nearly 20 percent in real terms over the past 16 years, and state and local funding for these programs has also generally declined. At the same time, EPA and state and local agencies face increasing demands on these limited resources, including (1) aging monitoring infrastructure, (2) expanded and low-value monitoring requirements, and (3) rising operating costs and competing priorities.

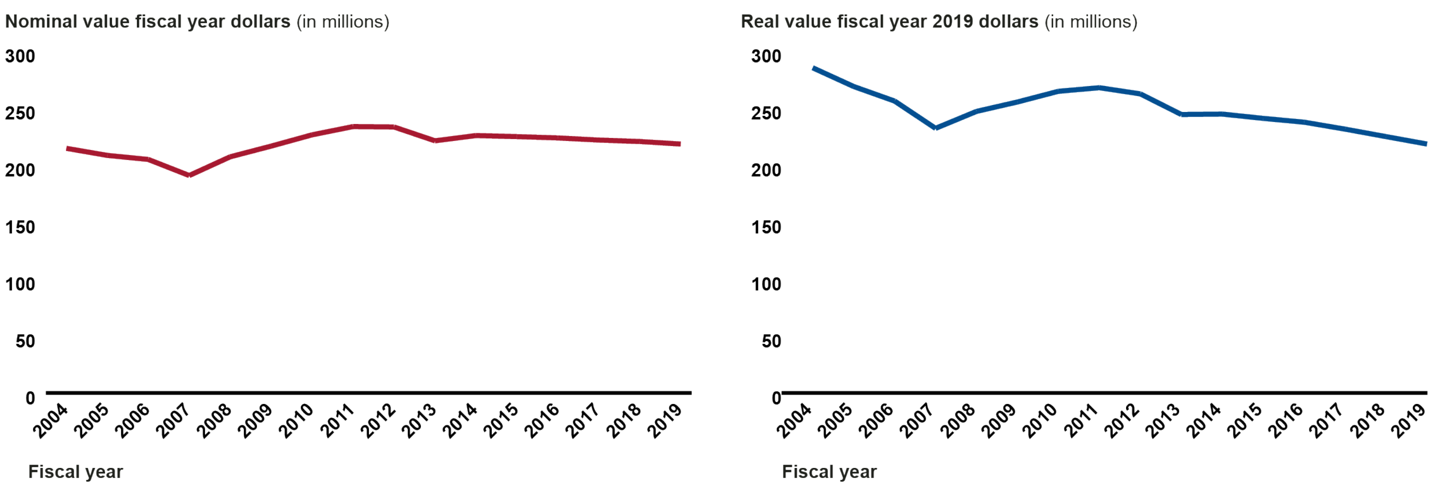
Declining Funding for Air Quality Monitoring Programs

Officials we interviewed from EPA and all of the selected state and local agencies and regional air quality associations said that they face

[36]According to EPA officials, state or local governments must provide matching funds when accepting Section 105 funds. The officials noted that the matching funds could be in another program or other acceptable form, but some form of state or local matching must occur.

significant challenges with funding for their programs, from both federal and nonfederal sources. First, the annual amount of federal grant funding that EPA provided for air quality management programs, which includes the national ambient air quality monitoring system, has remained relatively level over the past 16 years, varying from a low of approximately $190 million in 2007 to a high of approximately $230 million in 2011 and 2012 (see fig. 7). When adjusted for inflation, the amount of federal funding available for these grants declined on average by approximately $4 million per year between 2004 and 2019, resulting in an approximately 20-percent decrease in purchasing power for state and local agencies over this period.

Figure 7: Annual EPA Grant Funding for State and Local Air Quality Management, Which Includes Air Quality Monitoring



Source: GAO analysis of Environmental Protection Agency (EPA) and U.S. Department of Commerce, Bureau of Economic Analysis, data. | GAO-21-38

Note: The funding presented in this figure includes grants authorized under Sections 103 and 105 of the Clean Air Act. EPA provides this funding for air quality management programs, which includes air quality monitoring. Other activities funded by these grants include states' development of required programs, including air pollution emission control programs, to achieve attainment of the National Ambient Air Quality Standards. Real values are values adjusted for inflation and expressed in 2019 dollars using the U.S. Gross Domestic Product Price Index from the U.S. Department of Commerce, Bureau of Economic Analysis.

In addition, while the portion of monitoring costs covered by nonfederal funding varies significantly by state and locality, such funding has also been limited and declining, according to several representatives and officials we interviewed from national and regional air quality associations and state and local agencies. Representatives from a regional air quality association told us that some states are increasingly limiting the amount of state general funds provided to programs that have a source of federal funding. In addition, most of the 14 selected state and local agencies rely on funding from fees and penalties for their monitoring programs, but some state officials and regional air quality association representatives we interviewed said that funding from permit fees has been decreasing because some of the power plants required to obtain certain permits have been shutting down.[37] For example, according to a 2019 report from the Delaware Division of Air Quality, revenue from permits for major air pollution emissions sources decreased from a high of approximately $4 million in 2013 to just under $3 million in 2018.[38] Officials from Delaware told us that their monitoring program relies on permit fees to cover approximately half of the salaries for its monitoring staff. Finally, according to a representative of the National Association of Clean Air Agencies, the economic effects of the Coronavirus Disease 2019 (COVID-19) pandemic on state and local agencies' budgets will likely be dramatic and are already being felt.[39] The representative noted that some state and local agencies have already had to furlough air quality staff due to budget cuts.[40]

Officials and representatives we interviewed from all of the selected state and local agencies and all of the nation's regional air quality associations said that the current funding levels for air monitoring make it a challenge to sustain their monitoring programs and the level of service their networks provide. According to many of these officials and representatives, the funding trends have created a great deal of stress on

[37]Title V of the Clean Air Act requires that major sources of emissions for air pollutants obtain operating permits. Permitting authorities—including state and local agencies—collect fees from the sources required to obtain the permits.

[38]State of Delaware, Department of Natural Resources and Environmental Control, Division of Air Quality, *Annual Title V Fee Committee Status Report: Calendar Year 2018* (Delaware: May 1, 2019). This revenue funds many other state air quality activities in addition to air quality monitoring, including permitting, compliance, enforcement, and emissions inventory. According to officials from Delaware, the agency is seeking $3.84 million in Title V funding for the next 3-year cycle beginning January 1, 2021.

[39]The outbreak of COVID-19 was first reported in Wuhan, China, on December 31, 2019. In the weeks that followed, the virus quickly spread around the globe, and the World Health Organization characterized COVID-19 as a pandemic on March 11, 2020. The nation has experienced economic effects from the pandemic as millions have lost their jobs due to the stay-at-home orders and business closures aimed at reducing the spread of infections.

[40]According to EPA officials, in some cases, remaining staff are also being retasked to assist with assignments not related to monitoring. For example, according to the officials, some state and local air programs are housed within health departments, and staffing resources are being reallocated to account for increased COVID-19 demands.

monitoring budgets. Several state and local agency officials and regional air quality association representatives also said that the funding challenges forced agencies to triage their investments, often at the expense of the programs in the longer term. For example, representatives from one regional association noted that some of its member agencies have had to decide between hiring personnel to maintain needed staffing levels and upgrading to more efficient monitoring technology that could save resources in the longer term. In its budget justification documents for fiscal years 2020 and 2021, EPA has acknowledged this need for such trade-offs by stating that under the funding levels that EPA requested for State and Local Air Quality Management grants, "states will operate and maintain their air monitoring networks to the extent possible, balancing competing priorities."[41]

Aging Infrastructure

EPA and state and local agencies face challenges with aging infrastructure and the resulting increases in maintenance and operation costs, according to officials and representatives we interviewed from EPA, state and local agencies, and air quality associations. Officials from many of the state and local agencies said that that they had to use monitoring equipment well beyond its design life. In some instances, state agency officials said they were using equipment that was 15 to 20 years old. Monitoring equipment is generally designed to last for around 7 years, according to officials from one state agency.

As equipment ages, maintenance and operation becomes more difficult and expensive. Having old equipment creates such challenges as equipment no longer being serviced by the manufacturer or extra time and resources needed to maintain the equipment, according to some state and local agency officials. According to EPA officials from a regional office, one of the states in its region resorted to shopping on eBay to purchase used equipment parts that the manufacturer had discontinued. Officials from another state agency said that they have to cannibalize decommissioned equipment for parts to keep other equipment running. EPA officials noted that the aging equipment creates a vulnerability and has sometimes directly affected the quality of the data. For example, EPA officials said that several states had to invalidate ozone data for 2015 and

[41]EPA, *Fiscal Year 2020: Justification of Appropriation Estimates for the Committee on Appropriations*, EPA-190-R-19-002 (March 2019); and EPA, *Fiscal Year 2021: Justification of Appropriation Estimates for the Committee on Appropriations*, EPA-190-S-20-001 (February 2020).

2016 because old calibration equipment affected the quality of the data, leading to significant costs from the loss of valuable data.

Further, equipment using older technologies can be more expensive to operate in the long term, even if newer equipment has higher upfront costs, according to officials from several state agencies. Many state and local agencies continue to use older technologies for measuring particulate matter that require staff to visit the site, collect filters from the equipment, and send the filter to a laboratory for analysis. Equipment using newer, continuous methods for measuring particulate matter require no filter or laboratory analysis and provide the additional benefit of real-time data collection. However, officials from several state and local agencies cited barriers they face in moving to continuous methods.[42] For example, some agencies experienced technical issues with the EPA-approved equipment they purchased, such as having equipment overheat or not lasting over the long-term. Also, equipment using continuous methods tend to read higher levels of particulate matter than filter-based equipment.[43] These differences provide a disincentive to switch to continuous monitoring, particularly in areas that are currently below, but close to, the NAAQS, according to officials from some state and local agencies.

The supporting infrastructure for monitoring equipment—such as shelters and data loggers—is also aging. Officials from several state and local agencies noted that some of their shelters were up to 30 years old and in poor condition. Officials from one state agency said that, in some of their shelters, termites and ants are a constant issue and they have had to repair roof leaks with rubber cement and protect equipment with plastic sheets. Officials from this agency told us that the validity of monitoring data could be questioned if the conditions of the shelter affect the operation of the equipment. EPA officials noted that inadequate air conditioning in aging shelters can affect monitoring results, and officials from one state agency told us that air conditioning issues just recently

[42]In addition, EPA requires that a certain number of filter-based particulate matter monitors be located at the same site as continuous monitors for quality assurance purposes. According to EPA officials, this requirement prevents state and local agencies from moving completely away from filter-based monitoring. Therefore, these agencies must maintain the expertise to run and maintain these monitors and analyze the filters (or maintain contracts for laboratory analysis).

[43]Specifically, state agency officials said that, when using the manual method, certain types of particulate matter can volatilize from a filter before the filter is collected and sent to a laboratory for analysis. However, they noted that the continuous methods capture this volatile component.

affected a week's worth of ozone data. Figure 8 shows examples of aging monitoring infrastructure in Delaware and Louisiana.

Figure 8: Examples of Aging Monitoring Infrastructure

Exterior and interior of a monitoring site that is over 30 years old operated by the Delaware Department of Natural Resources and Environmental Control

Exterior and interior of a monitoring site that is 25 years old operated by the Louisiana Department of Environmental Quality

Source: GAO (top) and Louisiana Department of Environmental Quality (bottom). | GAO-21-38

While officials from many of the state and local agencies we interviewed said that they faced challenges with aging infrastructure, officials from some agencies said that they had successfully implemented plans to update their infrastructure. For example, officials from the Pennsylvania Department of Environmental Protection said they developed a multiyear plan in 2013 to modernize all of the equipment in its network. They said that the agency maintains a database of network asset needs and an asset replacement schedule. According to Pennsylvania officials, this enabled them to replace a significant amount of its assets over the past several years and resulted in a "state of the art" network. Similarly, around 2014, the Wisconsin Department of Natural Resources faced a staffing shortage due to a state hiring freeze, so officials developed an equipment replacement plan focused on purchasing equipment that could be remotely operated. As a result, according to Wisconsin officials, the state has a robust equipment replacement and inventory plan and has successfully automated a significant portion of the state's network. This has saved money on staff time that was formerly required to visit monitoring sites and has enhanced safety by keeping staff off of the road.

Expanded and Low-Value Monitoring Requirements

Officials we interviewed from several state and local agencies said that they face challenges implementing expanding requirements from EPA, which place increasing demands on resources. In some cases, EPA has added monitoring requirements without providing additional funds to manage and meet these requirements, according to officials from several state and local agencies.[44] For example, EPA has required that some state and local agencies implement enhanced monitoring of ozone and its precursors to improve understanding of ozone transport issues but has not provided additional funding.[45] Some state agency officials told us that enhanced ozone monitoring was important to help understand complex ozone issues, but it would require that resources be shifted from elsewhere. Further, some state and local agency officials told us that EPA has added additional criteria, but not resources, for operating air toxics monitoring within the national NATTS network. For example, in 2019, EPA added an air toxic—ethylene oxide—to the list of compounds to monitor at NATTS sites but did not increase the amount of funding provided to operate the NATTS sites. Officials from one state operating a NATTS site said that the annual laboratory costs for adding ethylene oxide was approximately $22,250. In some instances, state and local agencies have discontinued operation of their NATTS sites because, in

[44]According to EPA officials, in some cases, EPA has been able to provide funding for the initial purchase of equipment but has not been able to provide additional funding for the ongoing operational costs of the new equipment.

[45]In 2015, EPA revised 40 C.F.R, Part 58, Appendix D, to require state monitoring agencies with "moderate" and above 8-hour ozone nonattainment areas and states in the Ozone Transport Region to develop an Enhanced Monitoring Plan detailing enhanced ozone and ozone precursor monitoring activities to be performed to improve understanding of the ozone problems in the affected state.

part, they became too costly to operate, and the funding from EPA did not fully cover the costs.[46]

In addition, officials from some state and local agencies identified monitoring requirements that consume staff time and resources but, in their view, do not provide significant value. For example, even though the entire country currently attains the NAAQS for carbon monoxide, EPA requires some state and local agencies that were formerly out of attainment to monitor for carbon monoxide to ensure attainment continues, according to EPA officials.[47] However, several state agency officials we interviewed said that they considered carbon monoxide monitoring a low priority because the ambient levels were so low and the resources could be better used elsewhere.[48] In addition, several state and local agency officials we interviewed said they must purchase expensive, specialized equipment to meet stringent EPA calibration requirements for criteria pollutants found in their states at low levels.[49] According to some of the officials, this added cost and effort provides little value, since the pollution levels are well below the NAAQS.

Rising Operating Costs and Competing Priorities

Air quality monitoring costs continue to increase, and monitoring programs compete with other air quality management priorities for limited funding, according to documents we reviewed and several EPA and state and local agency officials. First, some officials told us that modern monitoring equipment technology is significantly more expensive than its predecessor technology. One piece of monitoring equipment can cost as much as $30,000, according to officials from one state agency. Finally, several state and local agency officials told us that personnel costs can be the largest cost within a monitoring program and, as officials from one agency noted, these costs are increasing. Monitoring program technicians need new skills to work with modern equipment and data systems, according to several state and local agency officials. Many positions now

[46]For example, Texas discontinued its two NATTS sites in 2019. Texas Commission on Environmental Quality officials told us that these sites became too expensive to operate after EPA added quality control requirements and enhanced requirements for the sensitivity of monitoring methods.

[47]These requirements are included in “maintenance plans” that state and local agencies develop to maintain the NAAQS.

[48]Despite generally low levels of carbon monoxide, some regional association representatives and state agency officials said that carbon monoxide monitoring data were also useful for evaluating air quality models.

[49]Calibrating equipment at a particular level helps to ensure that the instrument produces quality data at that level.

require advanced computing skills, and recruiting qualified workers can be challenging if the private sector pays higher salaries. According to several officials from EPA and state and local agencies, impending retirements in EPA and many state and local agencies will likely exacerbate some of these challenges as agencies try to hire staff with the skills to replace them.

Not only have the costs for air quality monitoring programs increased, but the costs and needs of other air quality management programs that use the same limited pool of funding resources have also increased in scope and complexity. For example, due to changes in the nature of air pollution, strategies to reduce that pollution have become more complicated and require more complex modeling, a better understanding of emissions sources, and increased stakeholder involvement. Representatives from one regional air quality association said that this has required that the agencies make trade-offs among air quality management programs.[50]

EPA Has Partially but Inconsistently Addressed Challenges in Sustaining the Monitoring System

EPA has initiated some informal efforts that have partially but inconsistently addressed the challenges that EPA and state and local agencies face in sustaining the monitoring system. Examples of EPA's efforts include:

- **Gathering information on monitoring infrastructure.** To help manage aging infrastructure, some selected EPA regions informally gather information from state and local agencies about the age and condition of the monitoring system's infrastructure. For example, officials from some EPA regions told us that they gather information about the condition of monitoring infrastructure through conversations with state and local agencies or that they informally check to see if their state and local agencies are tracking the condition of the equipment and have a replacement schedule. Also, officials from some regions said that they look at the age of state and local agencies' monitoring equipment informally during Technical Systems Audits or the annual grant cycle. However, EPA Office of Air Quality Planning and Standards officials said that the agency does not gather comprehensive and consistent information on the condition of monitoring infrastructure across the national system because EPA

[50]According to EPA officials, there are competing priorities at both the federal and state levels. For example, each administration has different priorities at the federal level—such as addressing backlogs of various air quality reviews—that may affect the attention and resources devoted to air monitoring. Similarly, according to these officials, state and local agencies may prioritize certain activities over air monitoring.

has not developed an approach for doing so. Some EPA officials told us that state and local agencies' annual monitoring network plan could be an effective mechanism for agencies to provide information on the age and condition of equipment. However, in our review of state and local agency annual monitoring network plans, only five of the 14 plans we reviewed reported any information to indicate the age of some equipment in the networks.

- **Incentivizing investments in continuous monitoring.** To help save resources in the long term, at least one EPA region has informally encouraged state and local agencies to transition to newer, continuous monitoring methods for measuring particulate matter that have lower long-term costs than older methods that use filters, according to officials from some state and local agencies. Officials we interviewed from two EPA regions said they have provided financial incentives for state and local agencies to make the transition by providing more funding for continuous monitors than for filter-based monitors—an effort that was successful in increasing the number of continuous monitors in at least one of the regions, according to EPA officials from the region. However, none of the other regional officials we interviewed reported using such incentives. In addition, EPA regulations require state and local agencies to report in their 5-year network assessments on incorporating new technologies into their networks, which provides a tool for EPA and state and local agencies to consider new technologies.
- **Reducing low-value monitoring.** Some EPA officials we interviewed said they have worked with state and local agencies to reduce low-value monitoring to maximize monitoring resources. For example, officials from Region 1 said their staff collaborated with state and local agencies to look for redundant monitors that could be discontinued, such as monitors in different states that cover the same metropolitan area. In addition, some EPA officials we interviewed said that EPA has worked with state and local agencies to reduce required monitoring of criteria pollutants no longer of national concern, such as carbon monoxide. Some EPA officials told us they were able to help state and local agencies discontinue carbon monoxide monitors by establishing proxy measures—such as traffic counts—that would indicate potential increases in carbon monoxide levels requiring further attention. As a result of these efforts, some state and local agencies were able to free up resources for other program needs. Nonetheless, officials from some state and local agencies told us that required monitoring they consider to have low value continues to consume staff time and limited resources.

An Asset Management Approach Could Provide Opportunities to Address Challenges More Consistently in Sustaining the Monitoring System

EPA's policy is to assure uniform enforcement of the Clean Air Act, a function in which the monitoring system plays a key role by providing data for comparison with air quality standards.[51] According to EPA officials, EPA has a responsibility to ensure that the monitoring system provides a consistent level of service across the country. However, as noted above, EPA has not consistently addressed the significant funding and resource challenges in sustaining the monitoring system. EPA's prior efforts to implement program-wide strategies that would help provide consistency across the monitoring system have been hindered when the agency had to shift limited resources to other priorities.

Our past work has suggested that employing an asset management approach could help EPA address challenges more consistently in sustaining the monitoring system. Specifically, we reported in March 2004 and November 2018 that asset management provides an approach to managing infrastructure that focuses on optimizing limited funding while sustaining the level of service needed from the assets.[52] This approach can help an organization develop an understanding of how each of its assets contributes to its success; manage and invest in those assets in such a way as to maximize that success; and foster a culture of effective decision-making through leadership support, policy development, and staff training.

In our March 2004 and November 2018 reports, we identified key characteristics of an effective asset management framework. EPA could more consistently address challenges in sustaining the monitoring system if its efforts better aligned with these key characteristics, such as:

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[51]EPA policy is to assure "fair and uniform application" by all regions of EPA criteria for enforcing the Clean Air Act. 40 C.F.R. § 56.3(a).

[52]GAO, *Water Infrastructure: Comprehensive Asset Management Has Potential to Help Utilities Better Identify Needs and Plan Future Investments,* GAO-04-461 (Washington, D.C.: Mar. 19, 2004); and *Federal Real Property Asset Management: Agencies Could Benefit from Additional Information on Leading Practices,* GAO-19-57 (Washington, D.C.: Nov. 5, 2018). According to the International Organization for Standardization, an asset is any item, thing, or entity that has potential or actual value to an organization. The International Organization for Standardization defines asset management as "the coordinated activity of an organization to realize value from assets." International Organization for Standardization, *ISO 55000 Asset Management—Overview Principles and Terminology* (Switzerland: 2014). The assets of the monitoring system include monitoring equipment, calibration equipment, computers and data processing systems, and monitoring station shelters.

- **Establishing plans to maximize assets and identify needed resources**. As we reported in November 2018, formal policies and plans that tie to an organization's mission and objectives can help the organization take a more strategic approach in making decisions about assets and identify resources required to implement the plans.[53] However, EPA has not established formal policies and plans for managing the assets of the national monitoring system nor has it identified the resource levels needed to consistently sustain the monitoring system's level of service. The agency has not done so because, as EPA officials noted, EPA has not taken a strategic and nationally consistent approach to managing the system's assets, along with state and local agencies, in a manner that maximizes the value of limited monitoring resources to meet EPA's goals and mission.[54]
- **Using quality data to manage infrastructure risks.** As we reported in March 2004 and November 2018, collecting information about capital assets—including age, condition, and level of service—helps managers identify their infrastructure needs and make informed decisions about the assets.[55] For example, managers can use the data on capital assets to assess risks and set priorities for replacement. EPA officials acknowledged that such a national picture of the condition of monitoring assets would be extremely valuable in managing the system to understand what investments are needed to maintain the system's desired level of service. However, EPA does not have this national picture because it has not established mechanisms to consistently gather information on monitoring assets across the country.
- **Targeting resources toward assets that will provide the greatest value.** As we previously reported, an organization should identify and target resources toward assets that will provide the greatest value in meeting its mission and strategic objectives.[56] For the monitoring system, an asset management framework could help EPA more consistently use available incentives across EPA regions to encourage states to invest in monitoring equipment that will provide the greatest value to the monitoring system. Such incentives include

[53]GAO-19-57.

[54]According to EPA officials, an asset management approach would have to closely involve the state and local agencies where officials would be invested in the process.

[55]GAO-04-461 and GAO-19-57.

[56]GAO-04-461 and GAO-19-57.

those that some EPA regions use to encourage state and local agencies to invest in continuous monitors for measuring particulate matter. A framework could also help EPA use available tools, such as network assessments, to assess new monitoring technologies for incorporation into the monitoring system. EPA officials noted that monitoring resources should be directed to the highest priority needs for sustaining the monitoring system. However, EPA has not been able to ensure resources are directed to the highest priorities because it does not have a comprehensive understanding of the system's investment needs or the costs and benefits of investing in different aspects of the monitoring system.

EPA officials told us that they believe the agency needs to more effectively plan for and invest in sustaining the monitoring system as a national asset in which the public has confidence. By working with state and local agencies to develop, make public, and implement an asset management framework that includes key characteristics such as identifying resources needed to sustain the monitoring system, using quality data to manage infrastructure risks, and targeting resources toward assets that provide the greatest value, EPA could better ensure that limited monitoring resources are targeted toward the highest priorities for consistently sustaining the monitoring system.

Air Quality Managers, Researchers, and the Public Need Additional Information in Four Areas to Better Understand and Address the Health Risks from Air Pollution

Air quality managers, researchers, and the public need additional information in four areas to better understand and address the health risks from air pollution, according to some literature we reviewed and officials from EPA and selected state and local agencies, representatives of national and regional air quality associations, and stakeholders. The information needs are (1) local-scale, real-time air quality; (2) air toxics; (3) persistent and complex pollution; and (4) using low-cost sensors and satellites.

Local-Scale, Real-Time Air Quality

Many EPA, state, and local agency officials; representatives of regional associations; and stakeholders identified the need for more local-scale, real-time information to meet evolving public demands. Some of these officials and stakeholders said that the increasing availability of other types of local-scale, real-time information—such as for traffic and weather—is creating a demand for local-scale, real-time air quality information so that individuals can make decisions to reduce their own risk. According to some literature we reviewed and several EPA and state and local agency officials we interviewed, the monitoring system is unable to meet all such needs.[57]

Specifically, according to these sources, the system is unable to meet needs for information on (1) air pollution hotspots, or local areas of high pollution; (2) short-term air quality changes in real-time; and (3) air quality in rural areas (see app. III for additional details). First, air pollution levels can change significantly from one location to another, and pollution hotpots may occur between existing monitoring sites.[58] In addition, some monitoring equipment in the system does not have the capability to provide real-time information. Finally, in rural areas, the distance between monitoring sites is often much greater than in urban areas, and some rural areas may not have any monitoring.

Air Toxics

The National Academies of Science, Engineering, and Medicine have long identified the need for more information, including monitoring data, to understand the risk posed by air toxics. Specifically, in a 2004 report on air quality management in the United States, the National Academies noted that exposure to air toxics was an important concern that is not well quantified due to limited information.[59] The report also noted the many unknowns associated with a large number of unlisted pollutants and the development and use of many new toxic substances each year make it challenging for the monitoring system to evolve quickly enough. More recently, in 2019, the California Air Resources Board identified over 800 new substances and proposed they be reported to assess air toxics risk.

[57]Currently, the AirNow program uses monitoring data from many existing monitors to create an AQI and help issue air quality alerts to provide timely air quality information to the public. In areas between monitors, EPA estimates the AQI based on the nearest monitors. AirNow calculates an AQI for current conditions based on particulate matter and ozone monitoring data.

[58]In populated urban areas, monitoring sites can be several miles apart and are often purposely located away from local sources of pollution to help ensure that they represent average air quality. For certain criteria pollutants, EPA requires that state and local networks include a monitor sited to measure the maximum concentration in an area, but these monitors may not capture information on all local hotspots.

[59]National Academies of Science, Engineering, and Medicine, *Air Quality Management in the United States,* The National Academies Press (Washington, D.C.: 2004).

According to some literature we reviewed and many stakeholders, officials from EPA and state and local agencies, and representatives of regional associations, specific needs include (1) air toxics information in key locations, (2) more timely information on air toxics, and (3) information on air toxics at low levels (see app. III for additional details). First, many stakeholders, representatives of regional associations, and officials from EPA and state and local agencies told us they need additional air toxics information in key locations near identified cancer clusters, environmental justice areas, industrial facilities, and other potential hotspots.[60] In addition, according to some of these sources, frequent air quality measurements that are available quickly are more useful for risk reduction and understanding sources. Finally, some methods for analyzing air toxics samples cannot detect air toxics at levels low enough to allow identification of potential public health threats.

Persistent and Complex Pollution

Many officials from EPA and state and local agencies and stakeholders said that they need more specialized information to better understand persistent and complex pollution issues to help identify options for reducing the pollution and its health effects. Understanding persistent or complex pollution issues often requires information that the monitoring system does not comprehensively provide, including information about pollution precursors and their sources, chemistry of the atmosphere, and transport of the pollutants.

Many EPA state and local agency officials and regional representatives of regional associations identified specific needs related to persistent and complex pollution that include information on (1) $PM_{2.5}$ and ozone formation and transport and (2) effects of wildfires on air quality and public health (see app. III for additional details). Although there are programs specifically designed to gather specialized information about $PM_{2.5}$ and ozone, many state and local officials and regional representatives of regional associations told us that they need additional information to help inform emissions control strategies.[61] Also, many stakeholders and officials from EPA and state and local agencies said

[60]Environmental justice areas are areas where disproportionately high health and environmental risks are found among low-income and minority communities.

[61]Emissions can mix with other substances in the environment to form other pollutants, so understanding interactions can be important for designing an emissions control strategy for a given area. The PAMS network provides information about the precursors and other factors that influence the formation of ozone, and the $PM_{2.5}$ Chemical Speciation Network (CSN) provides information on the chemical composition of particulate matter, which can help inform emissions control strategies.

that they need more information to better understand the complex effects of wildfires on air quality and human health.

Using Low-Cost Sensors and Satellites

Air quality managers, researchers, and the public are increasingly using emerging technologies to obtain information on air quality, but many EPA, state, and local agency officials; stakeholders; and regional representatives said that these users need more information on the reliability and accepted uses of these technologies. These technologies primarily include low-cost sensors—defined by EPA as sensors costing less than $2,500—and remote sensors on satellites operated by agencies such as the National Oceanic and Atmospheric Administration (NOAA) and the National Aeronautics and Space Administration (NASA). In another report, we have provided additional details on the opportunities and challenges associated with alternative air quality monitoring technologies, including low-cost sensors and satellites.[62]

Low-Cost Sensors

Low-cost sensors are increasingly available as a tool for both government agencies and the public to directly measure air quality because they can be deployed in many locations without significant initial investment. As a result, low-cost sensors have the potential to help meet some of the monitoring information needs that require pollution measurements in additional locations or more real-time data. To demonstrate and understand the use of sensors to gather information, we purchased five low-cost sensors from four different manufacturers and deployed them to measure $PM_{2.5}$ around the GAO building in Washington, D.C. (see fig. 9).

[62]See GAO, *Science & Tech Spotlight: Air Quality Sensors*, GAO-21-189SP (Washington, D.C.: Dec. 2020).

Figure 9: Low-Cost Sensors Deployed on the GAO Building

Sources: U.S. Geological Survey and GAO. | GAO-21-38

Officials from some state and local agencies said that their agencies use low-cost sensors to supplement their monitoring for limited purposes, but some had concerns about the quality of the information they produce.[63] In addition, many EPA and state and local officials said that they were aware of community groups, members of the public, private companies, or research groups using low-cost sensors. However, many EPA and state and local officials and regional representatives were also concerned about the need to ensure that these external stakeholders appropriately interpreted and applied information from low-cost sensors.[64] According to many EPA and state and local officials we interviewed, and as illustrated by our sensor demonstration, the public, government agencies, and researchers need additional information on how to use low-cost sensors and the data they produce, including information on (1) accepted and cost-effective applications of sensors, (2) proper sensor calibration, and (3) proper siting of sensors (see app. III for additional details). For example, as discussed in appendix III, our sensor demonstration illustrated the difficulty of measuring specific pollution levels without properly calibrating the sensors and the need to understand how the

[63]The sensors have been used for such applications as special studies related to wildfires, identifying sources, and engaging the community on pollution issues.

[64]EPA officials noted that, in some cases, private companies misinterpreted their low-cost sensor data. For example, according to EPA officials, a weather company used an indoor sensor that was mistakenly labeled as an outdoor sensor to describe the air in a particular county as unhealthy.

siting of the sensor can affect the data it produces to help avoid misinterpretation.

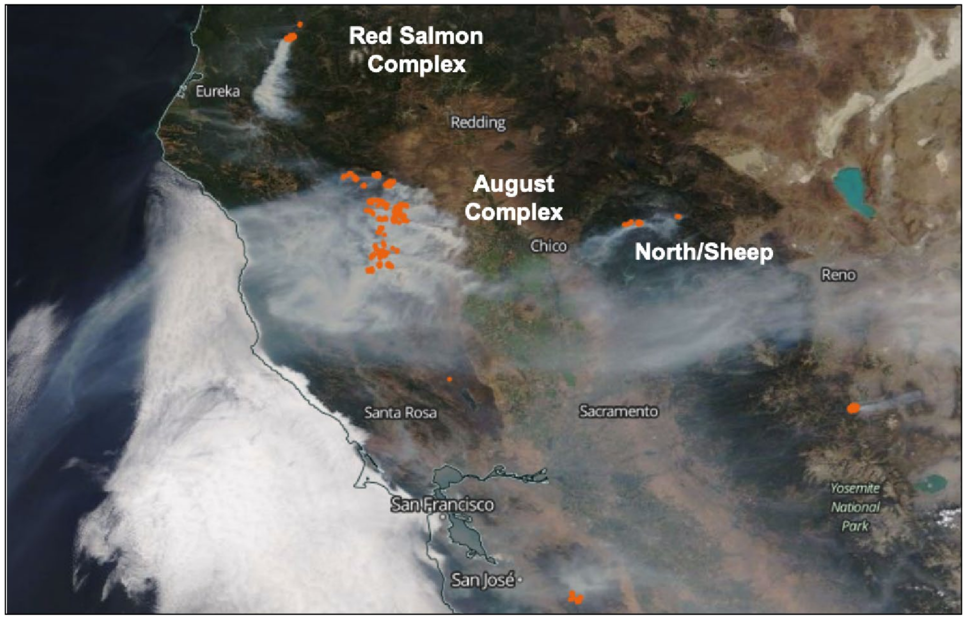
Satellites

Satellites can provide information on air pollutants over large areas, including areas that are difficult or impossible to monitor with traditional monitoring methods. According to some literature we reviewed and some stakeholders we interviewed, remote sensors on satellites currently provide information related to a few pollutants, including ozone, particulate matter, nitrogen dioxide, sulfur dioxide, and formaldehyde.[65] However, new satellite programs are increasing the availability of information that can be used to understand air quality.

Officials from some state and local agencies said that they use information from satellites to supplement air quality monitoring for limited purposes but said that they would likely increase their use of satellite data if they had more information on appropriate applications. For example, some state and local officials said that they had most commonly used satellite information for demonstrating the air quality influence of wildfires. However, with a better understanding of the applications, some state and local officials said they could also use satellite information to help track long-range transport of pollution, evaluate pollution levels in areas without monitors, and validate emissions inventories. Figure 10 shows satellite information indicating the locations of wildfire smoke in California.

[65]Sensors on satellites do not directly measure air quality; they generally measure energy reflected from or through the entire column of air above the earth. The data they collect must be processed with algorithms that use measurements from the ground to estimate ground-level air quality. In addition, satellite information is not always available at the scale and frequency that is needed. Some air quality data products are available from NASA and NOAA, but they generally require additional processing steps to be used in analyses of ground-level air quality.

Figure 10: Satellite Information Tracking the Movement of Wildfire Smoke



Source: National Aeronautics and Space Administration. | GAO-21-38

EPA and State and Local Agencies Face Persistent Challenges Meeting Additional Information Needs, and a Strategic Approach to Modernizing the Monitoring System Could Help Address Outdated and Incomplete Planning Efforts

EPA and state and local agencies face challenges in meeting additional air quality information needs that persist despite targeted efforts to address them. EPA has strategies aimed at meeting these information needs, but the strategies are outdated and incomplete. Our prior work suggests that a more strategic approach could help EPA and state and local agencies modernize the system to better meet additional information needs.

EPA and State and Local Agencies Face Challenges in Meeting Additional Air Quality Information Needs That Persist Despite Targeted Efforts to Address Them

EPA faces challenges in meeting additional air quality information needs that persist despite targeted actions to address them. The challenges persist in four key areas, which span across the air quality information needs: (1) establishing priorities for air toxics monitoring, (2) developing and improving air quality monitoring methods, (3) integrating emerging technologies, and (4) managing and integrating additional monitoring data.

Establishing Priorities for Air Toxics Monitoring

EPA and state and local agencies face challenges establishing priorities to help meet needs for additional information on air toxics. According to the National Academies and some EPA, state, and local officials, and regional representatives we interviewed, due in part to the large number of existing air toxics, monitoring for them needs to be prioritized. Some state and local agency officials also said that monitoring for air toxics needed to be prioritized because their budgets are mainly used to support required monitoring for criteria pollutants.[66] Specific prioritization challenges identified by EPA and state and local agencies, and the targeted efforts EPA has taken to address them, include the following:

- **Identifying air toxics that present the highest public health risks.** Some EPA and state and local officials told us that they have incomplete information about the public health risks associated with air toxics, making it difficult to understand which present the highest risks and might therefore be priorities for monitoring. Officials at some state and local monitoring agencies said that they look to EPA for help with prioritizing what to monitor in their areas.[67] For example, some EPA and state and local officials said that EPA's National Air Toxics Assessment provides information on potential air toxics risks in census tracts across the country and can inform decisions about air

[66]According to EPA officials, this focus on criteria pollutants directly relates to the structure of the Clean Air Act.

[67]EPA has community-scale air toxics grants that are intended to help states implement their priorities but do not establish priorities, according to EPA officials. EPA officials told us that the grant program includes some information about what types of projects will be funded, but these are intended to be broad and have not changed much over the life of the program.

toxics monitoring priorities.[68] However, the National Air Toxics Assessment has some limitations in informing such decisions. For example, it only estimates risk for a subset of air toxics.[69] In addition, the results of the assessment are based on emissions data from approximately 3 years prior, which limits its value for determining current needs for monitoring locations.[70]

- **Anticipating emerging air toxics issues.** Some EPA and state and local agency officials said that they face challenges in anticipating emerging issues with air toxics and prioritizing monitoring for those air toxics. The officials noted that monitoring for the air toxics associated with such issues has been reactive. An issue that recently emerged with ethylene oxide—an air toxic produced by medical sterilization facilities and other industries—illustrates this challenge. Specifically, in 2017, concerns emerged when a risk assessment identified elevated risks to public health from ethylene oxide in areas around the country where it was previously thought ethylene oxide posed low risk.[71] As a result, EPA added ethylene oxide to the list of monitored pollutants for NATTS sites and scrambled to better understand the

[68]The National Air Toxics Assessment uses information about the toxicity of pollutants along with emissions and monitoring data to assess air toxics risks. EPA's Integrated Risk Information System (IRIS) conducts assessments aimed at identifying and characterizing the toxicity of chemicals found in the environment. Each IRIS assessment can cover a chemical, a group of related chemicals, or a complex mixture. The U.S. Agency for Toxic Substances and Disease Registry and other organizations provide information on toxic substances.

[69]EPA officials noted that this is due in part to varying availability and quality of the data available through the National Emissions Inventory. As a result, EPA counsels against using the National Air Toxics Assessment to compare risks across states. We did not evaluate the quality or coverage of the National Emissions Inventory as part of this engagement.

[70]In addition, according to the National Academies, risk assessments are based on single pollutant risk and do not adequately reflect actual risk, which is driven by the mix of pollutants in the atmosphere, including criteria pollutants and air toxics. EPA officials published a joint risk assessment for air toxics and criteria pollutants with a limited scope that suggested integrating risk across pollutants would yield different monitoring and control priorities. See N. Fann, K. Wesson, and B. Hubbell, "Characterizing the confluence of air pollution risks in the United States" in *Air Quality, Atmosphere & Health*, vol. 9 (2016), 293. However, according to the assessment, it may be challenging to fully integrate risk assessments due to differences in how risk is expressed for various pollutants.

[71]In this case, a revision to the IRIS value for the toxicity of ethylene oxide was incorporated into the National Air Toxics Assessment, which showed that multiple communities were facing elevated risks. According to EPA officials, EPA's monitoring program needs better coordination with the IRIS program to maintain an awareness of any health risk values that may be changing.

risk by shifting staff from other priorities to work on ethylene oxide analyses and measurement methods, according to EPA officials. EPA officials said that they faced challenges in understanding and monitoring per- and polyfluoroalkyl substances (PFAS)—a group of manufactured chemicals—as concerns about emissions of PFAS into the air have emerged in some areas.

Developing and Improving Air Quality Monitoring Methods

Many EPA and state and local agency officials and regional representatives told us that they face challenges with the availability of adequate analysis methods to meet information needs, primarily for air toxics. They said that some existing analysis methods for pollutants are not sufficiently cost-effective, timely, or sensitive. For example, state officials said that laboratory methods for analyzing formaldehyde—a relatively common air toxic—are prohibitively expensive. In addition, some state agency officials and regional representatives said that continuous monitoring equipment is not available for some air toxics and is not cost-effective. Finally, as previously mentioned, some monitoring methods do not detect pollution at low enough levels needed to understand health effects.

EPA has programs to improve or develop new monitoring technologies, but these efforts have been targeted to specific monitoring purposes and have not fully addressed the challenges. According to EPA officials, these programs involve conducting in-house research through the Office of Research and Development and funding private sector work to develop technology for specific monitoring purposes, such as developing methods to monitor ethylene oxide and PFAS, and developing sensors for different pollutants or applications, including monitoring formaldehyde and providing information about air quality in and near wildfires.[72] In addition, according to EPA officials, the Office of Research and Development has updated only one air toxics monitoring method for air toxics in the past 20 years, and needs in this area exceed funding and capacity to address them.

Integrating Emerging Technologies

EPA and state and local agencies face challenges integrating emerging technologies into the monitoring system to help address needs related to real-time, local-scale information and using low-cost sensors and

[72]According to EPA officials, EPA also has a few small-dollar-value research programs related to emerging technology priorities, including the Regional Applied Research Program, which allows state and local monitoring agencies to work with EPA regions to conduct research on the regions' priorities, and the Pathfinder Initiative, which provides initial support for addressing emerging air quality issues to help start work on technical improvements.

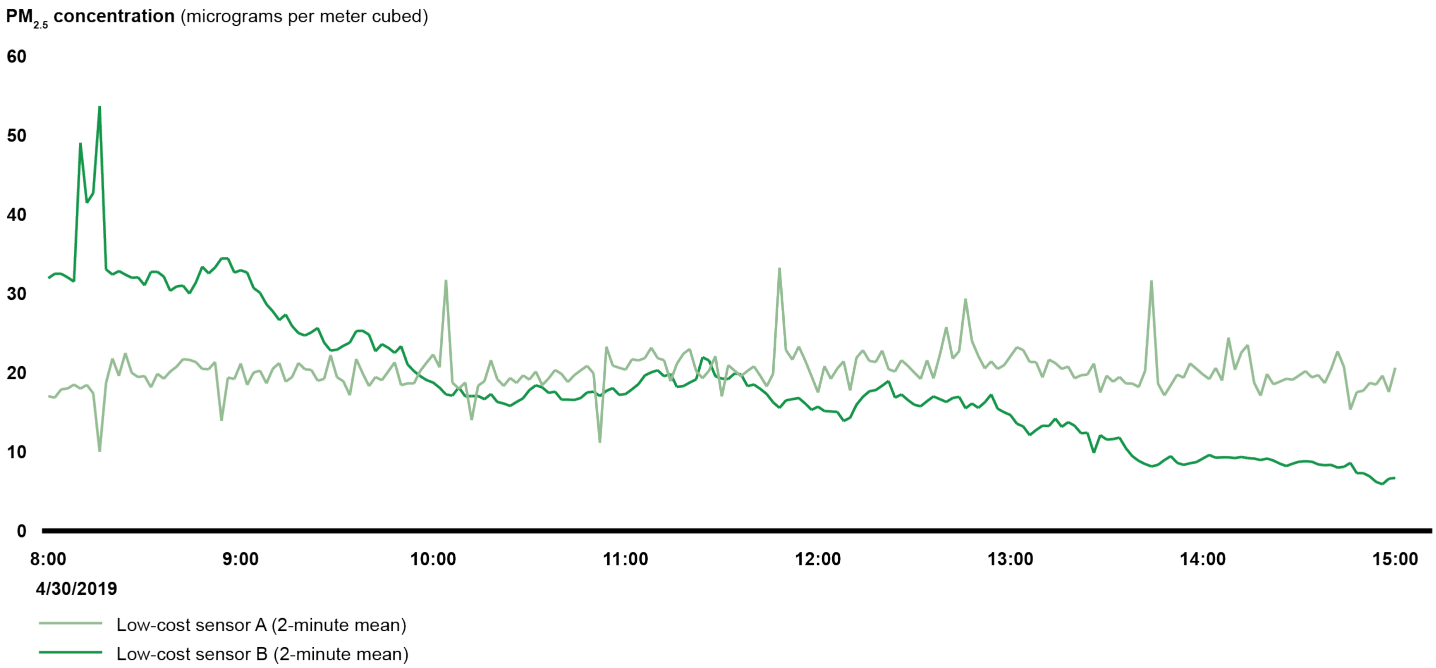
satellites. EPA has undertaken targeted actions to address them, but the challenges persist. For example:

- **Understanding the performance of low-cost sensors.** To meet information needs related to using low-cost sensors, air quality managers, researchers, and the public need to understand low-cost sensor performance. However, several EPA and state and local agency officials and stakeholders told us that users face challenges understanding differences in the quality of data that different types of low-cost sensors produce. According to some stakeholders and EPA and state and local agency officials, some low-cost sensors are considered relatively good at tracking overall pollution trends, while others were described as "random number generators." Various performance issues with low-cost sensor measurements have been documented, including issues with accuracy, interference from other pollutants, and variable performance in different temperature and humidity conditions. Starting around 2015, EPA's Office of Research and Development has worked with state and local monitoring agencies to co-locate sensors with EPA-approved monitoring equipment to study the performance of the sensors in specific environmental conditions, using the monitoring equipment as a baseline.[73] Our sensor demonstration illustrated that even when two different sensors are located side by side, they may produce different pollution measurements (see fig. 11).[74]

[73]According to our analysis of EPA data, as of July 2020, EPA has facilitated the deployment of at least 29 low-cost sensor models in 14 states. These include sensors that measure the criteria pollutants and volatile organic compounds, which can be air toxics and precursors to criteria pollutants. For additional information on some of EPA's projects, see https://www.epa.gov/air-sensor-toolbox/epa-air-sensor-research-overview, accessed Oct. 28, 2020. In addition, the South Coast Air Quality Management District conducts evaluations of low-cost sensors.

[74]When measured by EPA-approved monitors, the 24-hour health-based standard for $PM_{2.5}$ exposure is 35 micrograms per meter cubed, and the annual health-based standard for $PM_{2.5}$ exposure is 12 micrograms per meter cubed.

Figure 11: Differences in $PM_{2.5}$ Sensor Measurements from Two Sensors in the Same Location



Source: GAO analysis of GAO low-cost sensor data. | GAO-21-38

Note: $PM_{2.5}$ is particulate matter less than or equal to 2.5 micrometers in diameter. The data presented in the figure illustrate sensor differences over a short period of time, and this period is too limited to draw broad conclusions.

- **Communicating differences in low-cost sensor performance.** Several EPA and state and local agencies said they face challenges communicating to users about the performance of low-cost sensors.[75] To help ensure that information on the performance of low-cost sensors is available to air quality managers, researchers, and the public, EPA has targeted efforts under way to address challenges in communicating the performance of low-cost sensors. For example, EPA has developed an "Air Sensor Toolbox" that provides information on the performance, operation, and use of low-cost sensors.[76] In addition, EPA has held several workshops with the goal of issuing interim performance targets to provide manufacturers and the public

[75]For example, low-cost sensors have different averaging times that do not relate to health-based standards.

[76]See https://www.epa.gov/air-sensor-toolbox, accessed Oct. 28, 2020.

with a standardized way to compare low-cost sensor performance.[77] According to EPA officials, these performance targets will provide an interim baseline for organizations that set commercial standards to build off of to develop more comprehensive standards.[78] However, given that new low-cost sensors continue to become commercially available, communicating the performance of emerging low-cost sensors persists as a challenge, according to EPA officials.

- **Obtaining the expertise and resources to use information from satellites.** Officials from many state and local agencies said that they faced challenges in using satellite data because they did not have staff with the expertise or resources needed to access, process, and analyze the data. For example, measurements from remote sensors on satellites are not directly comparable to ground-based measurements of air quality for a number of reasons and require expertise to interpret.[79] Some state and local officials said that they would need training or user-friendly tools to build that expertise. Some state and local officials also said that they needed user-friendly information on where to obtain satellite data, the strengths and limitations of those data, and resources to process and interpret available data.[80] These challenges persist, despite some targeted EPA efforts to facilitate the use of satellite data. EPA has a cooperative agreement in place with NASA that identifies areas of cooperation to improve and facilitate the use of satellite information for monitoring air quality. For example, EPA works with NASA on a project that uses surface-based measurements to validate satellite

[77]Performance targets are a set of benchmarks that provide some basis to evaluate the quality information a sensor provides.

[78]ASTM International has standard-setting efforts underway. See ASTM WK64899: *New Practice for Performance Evaluation of Ambient Air Quality Sensors and Other Sensor-Based Instruments* (West Conshohocken, PA).

[79]Remote sensors on satellites provide information for the entire column of the atmosphere above an area on the earth. This information must be processed to estimate a measure of air quality at the ground level if it is to be used for air quality management purposes. Furthermore, satellite measurements represent an average over an area of 1 square kilometer or greater, which is different from standard, ground-based measurements that are taken at one location, according to some stakeholders and literature we reviewed.

[80]The NASA-funded Health and Air Quality Applied Science Team, funded through NASA's Applied Science Program, is a resource available to connect organizations working on air quality with potentially relevant satellite information and tools.

data.[81] EPA officials are also stakeholders on NASA's Health and Air Quality Applied Sciences Tiger Teams, and an EPA staff member is on detail to NASA.[82] EPA operates a data access tool, known as the Remote Sensing Information Gateway, which facilitates access to some satellite information, and incorporates some satellite information products into its AirNow platform.[83]

Managing and Integrating Additional Monitoring Data

EPA and state and local agencies face challenges meeting current data management needs that will likely persist into the future, according to some EPA and state and local officials. Some EPA and state and local agency officials said that the Air Quality System, EPA's data management system, barely meets current data management needs because the architecture of the system—which dates back to the 1990s—is antiquated and inflexible. According to EPA officials, the inflexibility of the Air Quality System makes it hard to make changes to the system to reflect the evolving data from the networks and produce data reports that meet users' needs. Some officials from state and local monitoring agencies identified challenges they face in managing data due to the architecture of the Air Quality System. For example, officials from one state said that that they faced many hurdles working with their state information technology system to create a custom solution that could transfer the data from their monitors to state servers and then prepare it for submission to the Air Quality System. Agency officials from another state said that the Air Quality System was not capable of accepting a particular data set from PAMS sites, so the state was storing the data on a laptop while EPA developed a solution. Some EPA and state and local officials also noted that increasing continuous monitoring for more pollutants will create substantially more data to manage, which could challenge the capabilities of the current system.

[81]The NASA Pandora Project coordinates and facilitates a global network of standardized, calibrated Pandora instruments that measure amounts of certain pollutants in the atmosphere. These pollutants absorb specific wavelengths of light from the sun in the ultraviolet-visible spectrum.

[82]According to EPA officials, EPA and NASA hold periodic meetings to discuss user needs for air quality measurements and to set priorities for incorporating satellite data into air quality management applications.

[83]https://www.epa.gov/hesc/remote-sensing-information-gateway.

EPA Has Strategies Aimed at Meeting Additional Air Quality Information Needs, but the Strategies Are Outdated and Incomplete

EPA has strategies aimed at better meeting the additional air quality information needs of air quality managers, researchers, and the public, including a 2004 strategy for air toxics monitoring, a 2008 strategy for state, local, and tribal air agencies, and a 2013 roadmap for next-generation monitoring.[84] These strategies included proposals to reconfigure and enhance the monitoring system's assets to better meet information needs, and EPA implemented some aspects of them.[85] For example, the 2008 strategy described how the National Core (NCore) network, which is now operational, would enhance understanding of the relationship between criteria pollutants and air toxics. In addition, the strategies describe many of the challenges that limit the monitoring system's ability to meet information needs and some steps to address them. For example, in its 2013 strategy, EPA identified the challenge that EPA and state and local agencies face in understanding the performance of low-cost sensors and steps to address them, such as conducting technology evaluations.

However, according to interviews with EPA officials and our review of the strategies, they are outdated and incomplete. EPA's strategies are outdated because they do not reflect additional information needs or changes in EPA's approaches and resources. In particular:

- Some of the additional information needs are not reflected in the monitoring strategies. For example, EPA's strategies do not address the use of remote sensing satellite information for air quality monitoring in any of the strategies. In addition, providing information on the effects of wildfires on air quality is not mentioned in the monitoring strategies. EPA has initiated some efforts to improve air quality monitoring near wildfires and to understand how to use

[84]EPA, Office of Air and Radiation, Office of Air Quality Planning and Standards, *Final Draft: National Monitoring Strategy: Air Toxics Component* (Research Triangle Park, N.C.: July 2004); EPA, Office of Air Quality Planning and Standards, *Ambient Air Monitoring Strategy for State, Local, and Tribal Air Agencies* (Research Triangle Park, N.C.: December 2008); and EPA, *Draft Roadmap for Next Generation Air Monitoring* (March 2013).

[85]According to EPA officials, EPA's *National Program Manager Guidance – Monitoring Appendix* offers direction and sets priorities for ambient air monitoring, including outlining the emerging needs identified in NAAQS reviews, while adhering to the themes in the monitoring strategies (see https://www.epa.gov/amtic/national-program-manager-npm-guidance-monitoring-appendix, accessed Oct. 30, 2020).

information from remote sensing satellites, but it is unclear how these fit into the overall strategy for meeting additional information needs.[86]

- Some of EPA's current approaches for meeting information needs are not reflected in any strategy. For example, although challenges related to low-cost sensors and steps to address them were included in the 2013 roadmap, they were not included in the 2004 or 2008 strategies, and none of the strategies fully reflects EPA's current approach to understanding and using low-cost sensors. In addition, EPA's strategies do not fully address challenges in meeting information needs, such as establishing priorities for air toxics monitoring.[87]
- Key efforts supporting the strategies were hindered because resources were diverted to other competing priorities. For example, community-scale monitoring grants were a key component of EPA's air toxics strategy for meeting the need to monitor air toxics in key locations. However, according to EPA officials, funding for these grants has been diminishing. The officials said that community-scale grants are the first to get squeezed out when funding gets constrained and, as a result, EPA does not offer them every year.[88] In addition, over the past decade, the Office of Research and Development's internal budget for air quality monitoring research, including methods development, has remained flat. According to EPA officials, methods development priorities must compete with other Office of Research and Development research priorities for resources. As a result, the Office of Research and Development is only able to take action on some of the monitoring technology research and development needs, and only one air toxics monitoring method has been updated in the past 20 years, according to EPA officials.[89]

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[86]In addition, according to EPA officials, EPA has developed the *Wildland Fire Research Framework 2019–2022* to outline research priorities and facilitate coordination with other federal partners.

[87]According to EPA officials, the larger air pollution community is doing a great deal of work on sensors but very little work on air toxics, yet the officials noted that the risk is likely in air toxics.

[88]According to EPA officials, EPA recently selected 11 air toxics monitoring projects to receive funding through the agency's community-scale monitoring grants.

[89]EPA method TO-15A is intended to (1) provide users with basic canister sampling and analysis information, (2) incorporate current technologies, (3) define performance criteria, and (4) recommend other procedures associated with 97 volatile organic compounds that are considered hazardous air pollutants.

In addition, EPA's strategies are incomplete because they do not consistently define roles and measures of success. In particular:

- Some roles for meeting additional information needs have not been clearly defined. For example, the 2004 air toxics strategy and the 2008 strategy do not clearly define the role of state and local agencies in providing input about certain priorities, including development and deployment of new technology. However, EPA officials told us that any successful air toxics approach would require significant input from state and local agencies. In addition, although EPA has better defined NASA's role in helping to meet information needs by signing a cooperation agreement with NASA, EPA does not have a similar agreement with NOAA. Some stakeholders also stated that satellite programs that are relevant to air quality monitoring would benefit from greater EPA involvement.
- Some measures of success in meeting additional information needs are unclear. For example, the 2004 air toxics strategy included a national-level goal of using monitoring to support air toxics problem identification by monitoring air toxics in key locations. Specifically, the community-scale air toxics program was included in that strategy to help improve monitoring in pursuit of that goal. However, EPA did not establish performance measures that help track progress at the national level and has faced challenges in anticipating and identifying problems.[90]

A More Strategic Approach to Modernizing the Air Quality Monitoring System Could Help EPA and State and Local Agencies Better Meet Additional Information Needs

Our prior work suggests that a more strategic approach to modernizing the monitoring system could help ensure that the system better meets additional air quality information needs and retains its value as a national asset. In our November 2018 report on asset management, we identified key characteristics of strategically managing an asset such as the air quality monitoring system, including that continuously evaluating how an agency manages its assets and implementing needed changes can optimize the value that the assets provide and ensure that they still reflect the organization's goals.[91] EPA officials said that meeting additional

[90]We have previously reported on key attributes of successful performance measures. For example, see GAO, *Environmental Justice: EPA Needs to Take Additional Actions to Help Ensure Effective Implementation*, GAO-12-77 (Washington, D.C.: Oct. 6, 2011). EPA established that each individual community-scale air toxics grant should have its own performance measures to evaluate the performance of each grant. However, it is unclear how those could be used to evaluate national level success.

[91]GAO-19-57.

information needs of air quality managers, researchers, and the public would require efforts to modernize the air quality monitoring system. In its strategies, EPA has recognized the need for an approach to modernizing the monitoring system that includes rethinking how best to manage the system to ensure that it reflects current air quality information needs.[92] However, EPA and state and local agencies face persistent challenges in modernizing the system, and its strategies to modernize the system to meet additional information needs are outdated and incomplete.

Developing a modernization plan that incorporates leading practices for strategic planning and risk management identified in our prior work could help EPA take a more strategic approach to meeting additional information needs. These leading practices and the ways they could help with a more strategic approach include:[93]

- **Establishing modernization goals and roles.** As we have previously reported, agencies should involve stakeholders to develop goals and strategies to help ensure that resources and efforts focus on the highest priorities.[94] Given the cooperative nature of managing the national ambient air quality monitoring system, partnering with state and local agencies in developing air quality monitoring modernization goals would help EPA ensure that modernization efforts target the most significant air monitoring information needs while also integrating priorities and emerging issues in different parts of the country. Multiple programs within EPA and across state and local agencies are vital for modernizing the monitoring system. For example, Office of Research and Development efforts to improve analysis methods can lead to adoption of improved technologies at state and local agencies that better meet new needs for information.

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[92]EPA, *Ambient Air Monitoring Strategy for State, Local, and Tribal Air Agencies* (December 2008).

[93]We have previously reported that strategic planning and risk management can help ensure that an organization identifies and successfully implements strategies to meets its goals and manages the risks that could impede meeting those goals. Our prior reports on leading practices for strategic planning include GAO, *Executive Guide: Effectively Implementing the Government Performance and Results Act,* GAO/GGD-96-118 (Washington, D.C.: June 1, 1996); *Managing for Results: Opportunities for Congress to Address Government Performance Issues*, GAO-12-215R (Washington, D.C.: Dec. 9, 2011); GAO-12-77; and *Nuclear Weapons: Additional Actions Could Help Improve Management of Activities Involving Explosive Materials*, GAO-19-449 (Washington, D.C.: June 17, 2019) .

[94]See, for example, GAO/GGD-96-118, GAO-12-215R, GAO-12-77, and GAO-19-449.

By assessing the extent to which relevant programs or activities can contribute to modernization and aligning these activities with one another and the modernization goals, EPA can help ensure that resources are being directed to the programs that will have the greatest impact on achieving modernization of the monitoring system. In addition, involving other federal agencies, such as NOAA and NASA, and identifying their role in supporting modernization of the system could help integrate new technologies, including satellites and sensors, into the monitoring system and better meet information needs.

- **Assessing risks to modernization success.** As we have previously reported, organizations should continuously and systematically assess the external and internal risks that affect the ability to achieve their goals.[95] Assessing these risks helps organizations anticipate future challenges and make adjustments before potential problems become crises. As previously noted in the report, various events—such as the sudden emergence of ethylene oxide as a national pollutant of concern—have exposed prioritization and technology challenges. A modernization plan with mechanisms to assess and plan for such risks could help EPA better manage these risks and minimize their impact on modernizing the monitoring system.
- **Identifying the resources needed to achieve modernization goals.** We have reported in our prior work that strategies should include a description of the resources needed to meet established goals.[96] Given the resource constraints on modernizing the monitoring system, identifying the resources needed to implement modernization efforts—such as expanding air toxics monitoring or updating data systems—would help EPA, state and local agencies, and Congress understand the level of investment required to implement various efforts within an air quality monitoring modernization plan, identify potential funding sources, and help ensure that resources are not diverted.
- **Measuring and evaluating progress.** As we have previously reported, performance measures should identify how well an organization is achieving its goals, and managers should use performance information to continuously improve organizational

[95]See, for example, GAO/GGD-96-118, GAO-12-215R, and GAO-19-449; and Department of Homeland Security, *National Infrastructure Protection Plan 2013.*

[96]See, for example, GAO/GGD-96-118, GAO-12-215R, GAO-12-77, and GAO-19-449.

processes, identify performance gaps, and set improvement goals.[97] We have also reported that government agencies often face a variety of competing demands that managers must take into account when measuring performance. This can help strike the difficult balance among competing demands and avoid overemphasizing some priorities at the expense of the others. By developing clear performance measures for modernization efforts, EPA and its partners can better ensure even progress toward each of the goals. In addition, by including mechanisms to regularly evaluate the effectiveness of the modernization plan, EPA can help align activities and resources with the modernization goals and ensure that progress continues.

An air quality monitoring modernization plan that aligns with these practices could help EPA and state and local officials build on and continue prior efforts to modernize the monitoring system. According to EPA officials, a successful air pollution monitoring modernization effort would identify resource needs and target resources at the highest priorities and identify and respond to information needs. By working with state and local partners to develop, make public, and continually improve upon an air quality monitoring modernization plan that aligns with leading practices, EPA can help optimize the value of the national ambient air quality monitoring system by better ensuring that it meets additional information needs and is positioned to protect public health as future air quality issues emerge.

Conclusions

The ambient air quality monitoring system is a valuable national asset that is essential for implementing the Clean Air Act and protecting public health from the effects of air pollution. EPA and state and local agencies cooperatively manage this system, and they face challenges in sustaining it in the face of decreasing funding and increasing demands on resources. EPA is responsible for ensuring that the monitoring system provides a consistent level of service across the country; however, we found inconsistencies across EPA regions in how EPA has addressed its management challenges. Our prior work has found that an asset management framework that includes key characteristics can help organizations optimize limited funding and sustain the level of service needed from assets. These key characteristics include establishing policies and plans to maximize assets and identifying needed resources, using quality data to manage infrastructure risks, and targeting resources toward assets that will provide the greatest value. EPA has not used these key characteristics in managing the monitoring system because it

[97] GAO/GGD-96-118.

has not taken a strategic and nationally consistent approach to managing the monitoring system, established mechanisms to consistently gather information on monitoring system assets across the country, or comprehensively identified monitoring system investment needs and trade-offs. By working with state and local agencies to develop, make public, and implement an asset management framework that includes key characteristics of asset management, EPA could better ensure that limited monitoring resources are targeted toward the highest priorities for consistently sustaining the system.

Air quality managers, researchers, and the public have needs for additional information about real-time, local-scale pollution; air toxics; persistent and complex pollution; and using emerging air quality measurement technologies. EPA faces challenges meeting these information needs, despite targeted efforts do so. In addition, EPA has strategies to help meet information needs that do not comprehensively reflect additional information needs and changes in EPA's approaches and do not consistently define roles and measures of success. By developing and making public a modernization plan for the national ambient air quality monitoring system, in conjunction with state and local agencies and other relevant federal agencies, that incorporates leading practices for strategic planning and risk management, EPA could optimize the value of the national ambient air quality monitoring system and ensure that it meets additional information needs and helps protect public health as future air quality issues emerge. These leading practices include establishing goals and roles, assessing risks to success, identifying needed resources, and measuring and evaluating progress.

Recommendations for Executive Action

We are making the following two recommendations to EPA:

The Assistant Administrator of EPA's Office of Air and Radiation, in consultation with state and local agencies, should develop, make public, and implement an asset management framework for consistently sustaining the national ambient air quality monitoring system. Such a framework could be designed for success by considering the key characteristics of effective asset management described in our report, such as identifying the resources needed to sustain the monitoring system, using quality data to manage infrastructure risks, and targeting resources toward assets that provide the greatest value. (Recommendation 1)

The Assistant Administrator of EPA's Office of Air and Radiation, in consultation with state and local agencies and other relevant federal agencies, should develop and make public an air quality monitoring modernization plan to better meet the additional information needs of air quality managers, researchers, and the public. Such a plan could address the ongoing challenges in modernizing the national ambient air quality monitoring system by considering leading practices, including establishing priorities and roles, assessing risks to success, identifying the resources needed to achieve goals, and measuring and evaluating progress. (Recommendation 2)

Agency Comments

We provided a draft of this report to EPA for review and comment. In its comments, reproduced in appendix IV, EPA generally agreed with our recommendations and stated that, if fully implemented, they would add value and help sustain the national ambient air monitoring program. In its comments, EPA also stated that, to assure success, it was important to engage stakeholders at the state, local, and tribal air monitoring agencies. In addition, EPA provided technical comments, which we incorporated as appropriate.

As agreed with your offices, unless you publicly announce the contents of this report earlier, we plan no further distribution until 25 days from the report date. At that time, we will send copies to the appropriate congressional committees, the Administrator of the Environmental Protection Agency, and other interested parties. In addition, the report is available at no charge on the GAO website at https://www.gao.gov.

If you or your staff have any questions about this report, please contact me at (202) 512-3841 or gomezj@gao.gov. Contact points for our Offices of Congressional Relations and Public Affairs may be found on the last page of this report. GAO staff who made significant contributions to the report are listed in appendix V.

J. Alfredo Gómez
Director, Natural Resources and Environment

Appendix I: Potential Topics for Future Air Pollution Oversight

Our evaluation of the national ambient air quality monitoring system revealed potential topics for future air pollution oversight work that we did not evaluate in detail in this report. Table 2 lists potential oversight topics compiled from literature we reviewed and our interviews with officials from state and local agencies, representatives from regional associations, and stakeholders.

Table 2: Potential Topics for Future Air Pollution Oversight

Related program/topic	Issue(s)
Air quality impacts on ecosystems	Air pollution can affect aquatic and terrestrial ecosystems through the deposition of pollutants from the air to the water or land. For example, one regional air quality association noted in a report that all of the states in the association's region have fish consumption advisories due to mercury contamination that likely originated from air pollution sources. According to representatives from a regional air quality association, more consistent monitoring is needed to track trends in and understand the sources and transport of the pollutants that can affect ecosystems.
Air quality management on tribal lands	As the Environmental Protection Agency (EPA) notes on its website, tribal citizens can often be disproportionately affected by air pollution and its health effects. Some EPA and state and local agency officials stated that they work with tribes to monitor local air quality and that tribes often have different monitoring needs and considerations than state and local governments.
Air quality management workforce	According to officials from EPA and a state agency, a significant number of staff in air quality management programs are nearing retirement, which will likely create a loss of expertise and institutional knowledge. Officials from several state and local agencies said they face challenges in hiring and retaining qualified staff to maintain a skilled air quality management workforce.
Air quality monitoring data management	Some EPA and state and local officials said that EPA's system for managing air quality monitoring data barely meets current needs because the architecture of the system is antiquated and inflexible. According to EPA officials, the inflexibility of the system creates significant barriers to getting the work done, and there are many lost opportunities by not moving to a cloud-based system. In addition, increasing volumes of data from newer technologies will likely further stress the current system.
Effects of wildfires on air quality	According to EPA officials and representatives from a regional association, the effect of wildfires on air quality is increasingly becoming a concern. Many stakeholders and officials from EPA and state and local agencies said they need more monitoring information to understand the effects of wildfires on air quality and health. The American Lung Association's 2019 State of the Air report showed that Americans are already experiencing worsened particle pollution due to increased wildfires and found that, as a result, climate change makes it harder to protect human health. Specifically, for several cities, the report showed spikes in unhealthy particle pollution episodes in 2019 driven by wildfires, noting that wildfire smoke caused one city to move from the list of cleanest cities to the list of most polluted cities.
Emissions inventory data quality and risk assessments	Some officials from EPA and state and local agencies told us that air quality emissions data reported through the voluntary National Emissions Inventory program are incomplete. The shortcomings can affect EPA's ability to assess the risks of air toxics to public health on a national basis.
Environmental justice in air quality management programs	Representatives from a regional association, officials from some state agencies, and a stakeholder noted various concerns regarding environmental justice in the context of air quality management. These include concerns that air toxics emissions may disproportionately affect disadvantaged communities and that communities most in need of alternative air monitoring tools, such as low-cost sensors, do not have access to them.
International air quality observation systems	According to some EPA officials, other countries, such as China, have successfully integrated artificial intelligence networks and sensors to provide continuous monitoring of air pollution. The experiences of these countries may provide some insight for modernizing the monitoring system in the United States.

Technology assessment of low-cost air quality sensors	As EPA officials noted, most commercially available low-cost sensors measure criteria pollutants, such as particulate matter less than or equal to 2.5 micrometers ($PM_{2.5}$) and ozone. However, relatively few sensors are available to measure air toxics. EPA officials we interviewed said that such technology for measuring air toxics would be valuable in filling in information gaps from the existing monitoring system. According to EPA officials, EPA has taken some limited steps to develop sensors but may not be fully taking advantage of potential technology developments across the federal government.
Understanding and managing international trans-boundary air pollution	Air pollution originating from international sources and transported to the United States can complicate efforts to manage air quality and affect the ability to attain National Ambient Air Quality Standards in some areas of the country. However, some officials from EPA and a state agency said that more information is needed to understand such pollution.
Using satellite information for air quality management	Satellite measurements can provide information on air pollution levels for certain pollutants and can be particularly useful for tracking movement of pollution over large areas. For example, information from satellites can be used to understand the movements of smoke from wildfires. However, as available satellite information continues to improve with new satellite programs, the useful applications of satellite information for air quality management will continue to expand. Such applications include identifying pollution sources, evaluating pollution transport, and validating emissions inventories.

Source: GAO analysis of information from literature and interviews. | GAO-21-38

Appendix II: Objectives, Scope, and Methodology

In this report, we examine (1) the role the national ambient air quality monitoring system plays in managing air quality and how the Environmental Protection Agency (EPA) and state and local agencies manage the system; (2) the challenges that EPA and selected state and local agencies face in managing the national ambient air quality monitoring system and the extent to which EPA has addressed and could better address these challenges; (3) what additional air quality monitoring information could help meet the needs of air quality managers, researchers, and the public; and (4) the challenges EPA and selected state and local agencies face in meeting air quality information needs and the extent to which EPA has addressed and could better address these challenges.

To address all of our audit objectives, we identified and reviewed federal laws and regulations governing the national ambient air quality monitoring system, such as the Clean Air Act Amendments of 1970;[1] EPA reports, guidance, and information on the oversight and operation of the monitoring system; and data on state and local monitoring networks from EPA's Air Quality System database. We also reviewed 10 studies and articles we identified through our own internet search and a literature review of databases, which primarily included academic journals; research by nonprofit organizations, such as the National Academies of Science, Engineering, and Medicine; and agency publications. The scope of our database search included literature published from 2014 through 2018 plus the beginning of 2019 that focused on (1) emerging air quality issues; (2) the performance of the national ambient air quality monitoring system; and (3) the state of new and alternative technologies for monitoring air quality, namely remote sensing satellite technology and low-cost sensors. The databases included ProQuest, Scopus, and DIALOG. We reviewed the literature to identify common themes related to our audit objectives. We also reviewed our past work on asset management, strategic planning, and risk management (references to this work are included in the report where the work is discussed).

In addition, we interviewed knowledgeable EPA officials from the Office of Air Quality Planning and Standards within the Office of Air and Radiation and the Office of Research and Development, and conducted a series of semistructured interviews with selected EPA regional offices and state and local air quality agencies. We first selected a nongeneralizable sample of six EPA regions in different parts of the country to provide a

[1]42 U.S.C. §7401 et seq. The Clean Air Act was significantly amended in 1977 and 1990.

range of characteristics that might be associated with various monitoring needs and design considerations, such as different air quality issues and population densities. We then selected two states in each region and three local areas to obtain a variety based on the same characteristics that can affect air quality monitoring—air quality issues, population density, and geography—as well as other characteristics, including monitoring of air toxics; use of emerging and automated technologies, such as sensors; and funding levels. We also reviewed the 5-year network assessments published in 2015 and the annual state plans published in 2019 for each state or local area in our nongeneralizable sample. Table 3 lists the states and local areas we selected in each EPA region. Our findings from these interviews cannot be generalized to other EPA regions or state and local agencies not included in the review.

Table 3: States and Local Monitoring Agencies by Environmental Protection Agency (EPA) Region Selected for Semistructured Interviews

EPA region	State or local area
Region 1 – Boston	Rhode Island
	Maine
Region 3 – Philadelphia	Delaware
	Pennsylvania
	Allegheny County, PA
Region 5 – Chicago	Wisconsin
	Illinois
Region 6 – Dallas	Texas
	Louisiana
Region 8 – Denver	Colorado
	Wyoming
Region 9 – San Francisco	Arizona
	Maricopa County, AZ
	South Coast Air Quality Management District, CA

Source: GAO. | GAO-21-38

We also conducted a series of semistructured interviews with officials from the two national and the six regional associations that represent state and local air monitoring agencies and assist them with implementation and technical issues associated with the Clean Air Act.[2] Table 4 lists these national and regional associations.

Table 4: National and Regional Associations Representing State and Local Air Monitoring Agencies

National organizations representing air monitoring agencies	
National Association of Clean Air Agencies (NACAA)	35 states, the District of Columbia, 4 territories and 116 local agencies
The Association of Air Pollution Control Agencies (AAPCA)	23 states and 25 local agencies
Regional organizations representing air monitoring agencies	
Central States Air Resource Agencies (CenSARA)	8 states and 7 local agencies
Lake Michigan Air Directors Consortium (LADCO)	6 states
Mid-Atlantic Regional Air Management Association, Inc. (MARAMA)	8 states and 2 local agencies
New England States for Coordinated Air Use Management (NESCAUM)	8 states
Southeastern Air Pollution Control Agencies (SESARM/METRO 4)	10 states and 17 local agencies
Western States Air Resources Council (WESTAR)	15 states

Source: GAO analysis of monitoring association websites. | GAO-21-38

To identify knowledgeable stakeholders with relevant expertise, in addition to conducting a literature search, we reviewed material from conferences and presentations, such as EPA's biennial National Ambient Air Monitoring Conference, and received referrals from government officials or other stakeholders. We selected and interviewed stakeholders based on their experience using air quality information and knowledge about the extent to which the monitoring system produces necessary air quality information. They included representatives of organizations focused on the health effects of air pollution, academic faculty, and representatives of private companies working on air quality technologies. Our findings from this nongeneralizable sample cannot be generalized to other stakeholders we did not interview. In addition, the specific areas of expertise varied among the stakeholders we interviewed, so not all of the stakeholders commented on all of the interview questions we asked. Table 5 lists the organizations of the knowledgeable stakeholders selected for semistructured interviews.

[2]The six regional associations are known as Multi-Jurisdictional Organizations and are funded primarily by EPA grants to the states under Section 105 of the Clean Air Act. They serve as regional liaisons between state, local, and tribal air agencies; EPA regional offices; and EPA national offices. They also work with their state air agencies on such services as modeling, monitoring, data analysis, and training.

Table 5: Organizations of Knowledgeable Stakeholders Selected for Semistructured Interviews

Research organizations:
American Lung Association
Health Effects Institute
Private companies:
PurpleAir, LLC.
QuantAQ, Inc.
TD Environmental Services, LLC
Academic institutions (stakeholders representing their own views, not those of their organizations):
Carnegie Mellon
Cornell University
Emory University
University of Southern California
University of Wisconsin—Madison

Source: GAO. | GAO-21-38

Finally, to address our third and fourth audit objectives—to help identify additional information that air quality managers, researchers, and the public need and the challenges in modernizing the monitoring system to meet user needs—we conducted our own demonstration of sensor technologies by purchasing five low-cost air quality sensors and deploying them outside of the GAO building in Washington, D.C. To conduct the sensor demonstration, we selected, purchased, and installed five low-cost sensors around the GAO building in two locations. Our selection criteria for the sensors included (1) commercial availability, (2) a cost of less than $500, (3) the ability to measure a pollutant that is commonly measured in the monitoring system, (4) suitability for outdoor use, and (5) offline data logging and recovery capabilities. We selected particulate matter less than or equal to 2.5 micrometers in diameter ($PM_{2.5}$) as the target pollutant because of its year-round variation and then identified 28 potential sensors using two sources: the South Coast Air Quality Management District Sensor Performance Evaluation Center and additional internet searches for sensors. Based on the selection criteria, we narrowed down the list of candidate sensors to four models that met these criteria and had a variety of features, such as outdoor suitability, data recovery method, and output measurement unit: Dylos DC1700, Purple Air PA-II-SD, ECOWITT WH0290, and Airbeam2. We purchased two Purple Air sensors and one of each other sensor model.

In selecting sites for sensor installation, we considered EPA guidance on sensor placement available to the public, subject to the physical constraints associated with the GAO building.[3] GAO installed four of the sensors in two fixed locations on opposite sides of the building. The sensors were located approximately 7 feet off the ground on small out buildings that were 10 to 20 feet away from the main building but not near any known, continuous source of air pollution from the building. These locations were close to entrance ramps to the parking garage that were busier at peak commuting times and were potentially influenced by delivery trucks in their immediate vicinity on occasion. The Purple Air sensors operated from April 2019 to March 2020, and the other fixed sensors operated from April to June 2019. In addition, we used one sensor—the Airbeam2—as a mobile monitoring device. We did not take steps to calibrate the low-cost sensors during this period and performed only the maintenance required to keep them operating and recover data. Each low-cost sensor measures multiple air quality parameters.[4] We chose to record information on $PM_{2.5}$ in micrograms per cubic meter in order to facilitate comparisons.

We conducted this performance audit from March 2018 to November 2020 in accordance with generally accepted government auditing standards. Those standards require that we plan and perform the audit to obtain sufficient, appropriate evidence to provide a reasonable basis for our findings and conclusions based on our audit objectives. We believe that the evidence obtained provides a reasonable basis for our findings and conclusions based on our audit objectives.

[3]R. Williams, et al., *Air Sensor Guidebook.* EPA/600/R-14/159 (NTIS PB2015-100610) (Washington, D.C.: U.S. Environmental Protection Agency, 2014).

[4]For example, multiple sensors provide measures of PM_1, $PM_{2.5}$, and PM_{10}. The Purple Air sensors contain two sensors, each producing its own readings, and output data using two different correction factors.

Appendix III: Additional Information on Air Quality Monitoring Information Needs

This appendix provides additional information on the information needs discussed in the report: (1) local-scale, real-time air quality; (2) air toxics; (3) persistent and complex pollution; and (4) using low-cost sensors and satellites.

Local-Scale, Real-Time Air Quality

Some literature we reviewed and many Environmental Protection Agency (EPA) and state and local agency officials, representatives of regional associations, and stakeholders identified the need for more local-scale, real-time information to meet evolving public demands. Specifically, they identified the following:

- **Information on air pollution hotspots.** Air pollution levels can change significantly from one location to another, and pollution hotpots—local areas of high pollution—may occur between existing monitoring sites.[1] Several state and local agency officials and representatives of regional associations said that members of the public contact agencies for information regarding air quality in specific locations. For example, some state and local agency officials said that members of the public had contacted them asking for information about pollution from a quarry, industrial facility, or oil and gas facility. Furthermore, according to some public health researchers we interviewed, they need air quality information on a localized scale to get an accurate picture of the exposure that individuals face and the associated health effects. Some state and local officials said that they used mobile air quality monitoring units—such as monitoring equipment set up in movable vans or trailers (see fig.12)—to temporarily monitor in certain areas.

[1]In populated urban areas, monitoring sites can be several miles apart and are purposely located away from local sources of pollution to help ensure that they represent average air quality. For certain criteria pollutants, EPA requires that state and local networks include a monitor sited to measure the maximum concentration in an area, but these monitors may not capture information on all local hotspots.

Figure 12: Example of a Mobile Air Quality Monitoring Unit

Exterior and interior of a mobile monitoring unit operated by the Delaware Department of Natural Resources and Environmental Control

Source: GAO. | GAO-21-38

- **Real-time information on short-term changes in air quality.** Air quality managers and the public need more frequent measurements that can be reported in real time, according to some literature we reviewed and several stakeholders and officials from EPA and state and local agencies. Not all monitors are able to report information in real-time. For example, particulate matter monitors that use manual, filter-based methods provide data once over a 24-hour period, as opposed to hourly for continuous monitors. In addition, officials from some state agencies told us that receiving results of the filter-based monitoring from the laboratory can take anywhere between 1 week and 2 months. According to EPA officials, in 2019, approximately 48 percent of particulate matter less than or equal to 2.5 micrometers in diameter ($PM_{2.5}$) monitors used these filter-based methods. Obtaining real-time information could help air quality managers and the public understand short-term changes in air quality due to changes in weather patterns or events, such as natural disasters and industrial accidents. Some state and local agency officials stated that members of the public had contacted them after disasters or industrial accidents. However, according to a report by the EPA Inspector General, providing that information can be challenging.[2]
- **Air quality information in rural areas.** In rural areas, the distance between monitoring sites is often much greater than in urban areas, and some rural areas may not have any monitoring. EPA's Clean Air Act regulations establish population as a factor in designing criteria

[2]EPA's Office of Inspector General issued a report on the need for EPA guidance on monitoring after disasters. See EPA, Office of Inspector General, *EPA Needs to Improve Its Emergency Planning to Better Address Air Quality Concerns During Future Disasters,* Report #20-P-0062 (Washington, D.C.: Dec. 16, 2019).

pollutant monitoring networks, which has resulted in more monitoring sites being located in urban areas than in rural ones. However, according to some state and local agency officials and representatives of regional associations, limited monitoring in rural areas makes it difficult to fully understand the air quality issues that can have an acute effect on air quality in those areas, such as wildfires, oil and gas development, and wood smoke in mountain valleys. According to EPA, 2,120 of 3,142 counties in the United States had no ambient air quality monitor associated with the monitoring system in 2019.[3]

Air Toxics

According to some literature we reviewed and many stakeholders, officials from EPA and state and local agencies, and representatives of regional associations, specific needs for information on air toxics include the following:

- **Air toxics information in key locations.** Many stakeholders, representatives of regional associations, and officials from EPA, state, and local agencies told us that they need additional air toxics information in key locations near identified cancer clusters, environmental justice areas, industrial facilities, and other potential hotspots.[4] For example, one researcher we interviewed said that the research community needs more detailed information about the types of particles that comprise particulate matter pollution to understand their public health effects. Another researcher's organization has supported efforts to gather more air toxics data outside of the monitoring network because the current network cannot fully meet the organization's needs. Air toxics pollution tends to be more localized than pollution from criteria pollutants, so air toxics monitoring needs to be concentrated in key locations, according to some literature we reviewed, and some EPA officials, stakeholders, and representatives of regional associations. However, an EPA Inspector General report from 2005 found that some areas with a relatively high risk from air toxics emissions are not being monitored.[5]

[3]"Counties" includes other similar administrative units, such as parishes and independent cities. EPA officials added that unmonitored areas can be more consequential in areas of changing terrain or varying meteorological conditions, which can affect the distribution of pollution.

[4]Environmental justice areas are areas where disproportionately high health and environmental risks are found among low-income and minority communities.

[5]EPA, Office of Inspector General, *Progress Made in Monitoring Ambient Air Toxics, But Further Improvements Can Increase Effectiveness*, 2005-P-00008 (Washington, D.C.: Mar. 2, 2005).

- **More timely information on air toxics.** Frequent air quality measurements that are available quickly are more useful for risk reduction and understanding sources. Like $PM_{2.5}$ filter-based monitors, most air toxics samples are sent to laboratories for analysis, which, as previously discussed, takes time. In addition, monitoring for air toxics often uses canisters or other sampling devices that capture air over a defined amount of time, such as over a 24-hour period, which can make it difficult to understand which sources emitted the air toxics affecting that location throughout the day. All air toxics samples at National Air Toxics Trends Stations (NATTS) are collected over a 24-hour period once every 6 days.
- **Information on air toxics at low levels.** Some methods for analyzing air toxics samples cannot detect air toxics at levels low enough to allow identification of potential public health threats. Specifically, according to EPA officials, two out of the 19 core air toxics have methods with a detection limit that is above or near the level that would be relevant for assessing health effects.[6] In such cases, officials cannot conclusively identify whether the air toxics present a public health risk. An inconclusive result is difficult to explain to the public, according to some state and local agency officials.

Persistent and Complex Pollution

Many EPA and state and local agency officials and representatives of regional associations identified specific needs related to persistent and complex pollution, which include the following:

- **$PM_{2.5}$ and ozone formation and transport.** Although there are programs specifically designed to gather specialized information about $PM_{2.5}$ and ozone formation, many state and local officials and representatives of regional associations told us that they need additional information to help inform emissions control strategies.[7] For example, officials from agencies in multiple states and regions mentioned the need for additional information, such as information at

[6]Acrolein and ethylene oxide have detection limits that are above health-relevant levels. Core air toxics refers to the NATTS Tier I analytes, which are a group of 19 air toxics that have been identified as major risk drivers based on a relative ranking performed by EPA. EPA officials reported that the agency has taken some steps to improve monitoring methods for air toxics.

[7]Emissions can mix with other substances in the environment to form other pollutants, so understanding interactions can be important for designing an emissions control strategy for a given area. Photochemical Assessment Monitoring Stations (PAMS) provide information about the precursors and other factors that influence the formation of ozone, and the $PM_{2.5}$ Chemical Speciation Network (CSN) provides information on the chemical composition of particulate matter, which can inform emission reduction strategies.

multiple heights, to determine the causes of elevated ozone levels near large bodies of water, such as the Great Lakes. Some state and local officials said that they need additional meteorological equipment at monitoring sites to help pinpoint pollution sources and understand how pollution moves through an area.

- **Effects of wildfires on air quality and public health.** Many stakeholders and officials from EPA and state and local agencies said that they need more information to better understand the complex effects of wildfires on air quality and human health. Emissions from wildfires can include many different pollutants, such as certain air toxics, which the current monitoring system does not routinely monitor. In addition, wildfires create acute air quality problems, including in rural areas that are located away from existing monitoring infrastructure, while also affecting air quality hundreds of miles away. Finally, long-range transport of pollutants from wildfires makes it more challenging to disentangle the effect of local sources of pollution. More widespread monitoring could help air quality managers better understand the effects of wildfire smoke as it moves through communities.

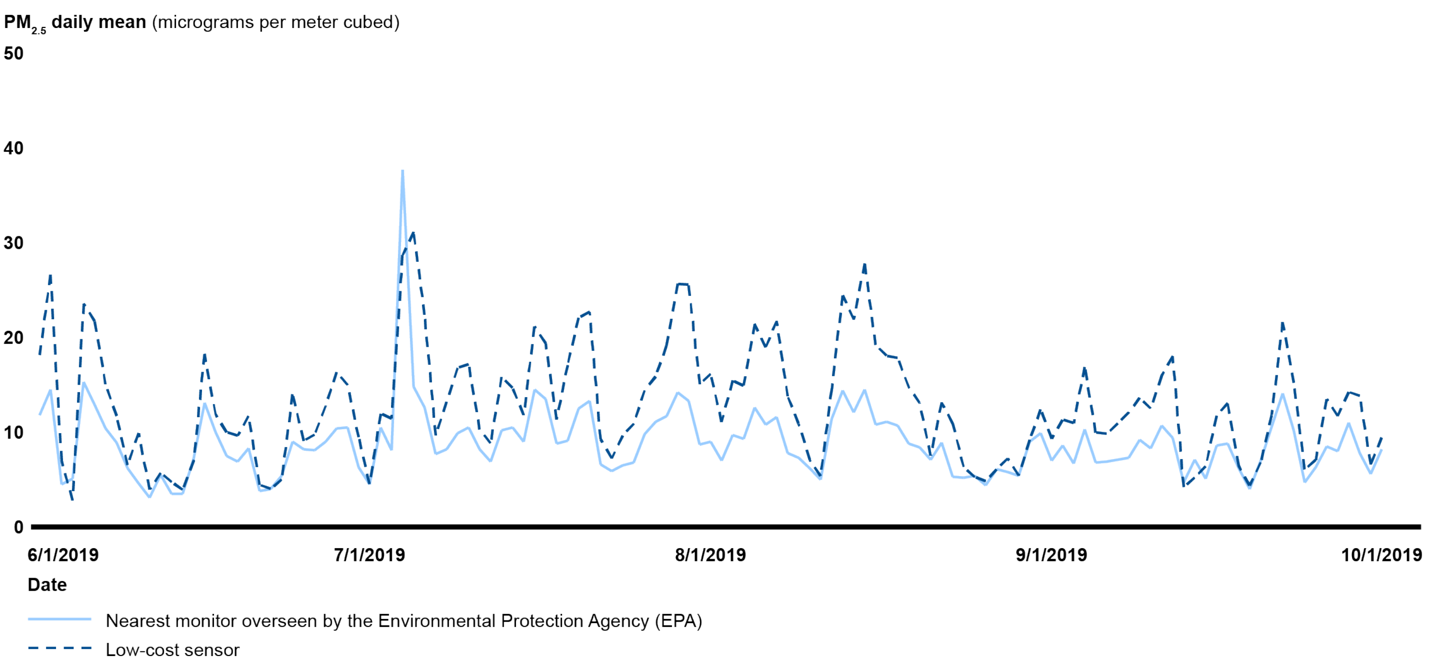
Using Low-Cost Sensors and Satellites

According to several EPA and state and local officials we interviewed, and as illustrated by our sensor demonstration, the public, government agencies, and researchers need additional information on how to use low-cost sensors and the data they produce, including:

- **Accepted and cost-effective applications of sensors.** Many state and local officials we interviewed said that they saw potential for using low-cost sensors in the future for applications, such as identifying ideal locations for regulatory monitors, locating pollution hotspots, supporting community-based monitoring initiatives, expanding air toxics monitoring, addressing citizen concerns and questions, and tracking wildfire smoke. Although some officials we interviewed from state and local agencies had used sensors to support their own air quality management work, officials from several state and local agencies said that they would not likely invest significant resources in sensor technology until more information was available about how to use low-cost sensors in specific applications or until EPA has endorsed the specific applications. In addition, several state and local officials said that information on durability and performance over the lifespan of a low-cost sensor is needed to evaluate its suitability for these applications. Several stakeholders and state and local officials had concerns about the cost-effectiveness of deploying networks of sensors to meet information needs.

- **Proper sensor calibration.** Many EPA and state and local agency officials expressed concerns that members of the public may misinterpret information from uncalibrated sensors and question why the sensor data differ from regulatory monitoring data. Several stakeholders and EPA and state and local officials noted the need for widely available information on how to appropriately calibrate sensors. Some state and local officials and stakeholders expressed concerns about the ability of users to calibrate low-cost sensors to ensure that performance is consistent over time. We found that one of our sensors did not come with information on calibration. In addition, data from another low-cost sensor generally measured higher levels of $PM_{2.5}$ when compared with data from the nearest EPA-overseen monitor located approximately 2 miles north (see fig. 13). Without the ability to properly calibrate this low-cost sensor, we could not determine with certainty whether actual pollution levels are consistently higher at that location.

Figure 13: Comparison of $PM_{2.5}$ Data from a Low-Cost Sensor on the GAO Building and an EPA-Overseen Monitor 2 Miles Away

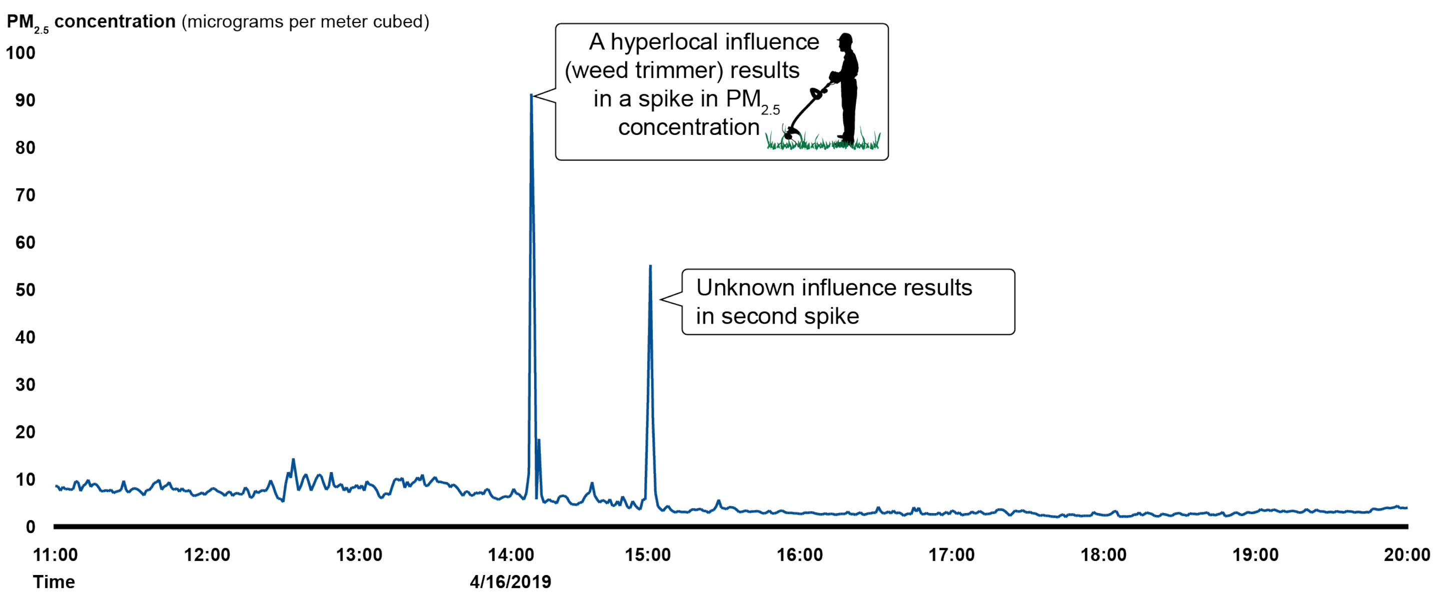


Source: GAO analysis of GAO low-cost sensor data and EPA-overseen monitor data. | GAO-21-38

Note: $PM_{2.5}$ particles are particles with a diameter of 2.5 micrometers or less. When measured by EPA-overseen monitors, the 24-hour health-based standard for $PM_{2.5}$ exposure is 35 micrograms per meter cubed, and the annual health-based standard for $PM_{2.5}$ exposure is 12 micrograms per meter cubed.

- **Proper siting of sensors.** Some stakeholders and officials from EPA and state and local agencies noted the need for information on how to site low-cost sensors to increase the reliability of the data. Some stakeholders and state and local officials said that low-cost sensor users need to account for factors associated with a sensor's location and specific local sources of pollution that can influence sensor measurements. We found that a sensor we deployed for our demonstration measured temporary spikes in particulate matter due to a gas-powered weed trimmer that we observed being used directly underneath the low-cost sensor (see fig. 14). Proper interpretation of the sensor data requires tracking and accounting for these local influences.

Figure 14: Local Influences on Measurements from a Low-Cost Sensor on the GAO Building



Source: GAO analysis of GAO low-cost sensor data. | GAO-21-38

Note: $PM_{2.5}$ particles are particles with a diameter of 2.5 micrometers or less. When measured by EPA-overseen monitors, the 24-hour health-based standard for $PM_{2.5}$ exposure is 35 micrograms per meter cubed, and the annual health-based standard for $PM_{2.5}$ exposure is 12 micrograms per meter cubed.

Appendix IV: Comments from the Environmental Protection Agency

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D.C. 20460

October 27, 2020

OFFICE OF
AIR AND RADIATION

Mr. Alfredo Gomez
Director
Natural Resources and Environment
U.S. Government Accountability Office
Washington, D.C. 20548

Dear Mr. Gomez:

Thank you for the opportunity to review and comment on the U.S. Government Accountability Office (GAO) Draft Report (GAO-21-38), *Air Pollution - Opportunities to Better Sustain and Modernize the National Air Quality Monitoring System.* The purpose of this letter is to provide the U.S. Environmental Protection Agency's (EPA) response to GAO's recommendations as well as share our technical corrections and comments noted in Enclosure 1.

EPA generally agrees with the GAO's recommendations; however, as explained below, we will want to work very closely with our state, local and tribal air agency partners to solicit their input on what they need to ensure success in improving the ambient air monitoring program. It should also be recognized that full implementation of the recommendations would require additional resources; especially additional funding for state, local and tribal air agencies to purchase new equipment. The availability of these resources must be a major consideration in sustaining and improving the national ambient monitoring program.

The draft report found that "the ambient air monitoring system is a national asset that provides standardized information for implementing the Clean Air Act and protecting public health." While the draft report identified several challenges related to sustaining the monitoring system, such as aging infrastructure and declining grants due to inflation over time, and inconsistencies in how EPA's Regional offices have addressed these challenges, there are examples of states that have successfully navigated this process. The draft report offers two recommendations intended to help address these issues.

We have circulated the draft report to key EPA offices that work on or support the national ambient air monitoring program and an enclosure provides detailed technical comments for the GAO's consideration from the following offices: EPA's Office of Air Quality Planning and Standards, Air Quality Assessment Division; EPA's Office of Research and Development; EPA's Office of Atmospheric Program, Clean Air Markets Division; and EPA Region 8 (lead Region on Ambient Air Monitoring).

Below find each of the GAO's recommendations to EPA for executive action, our response, and our notes and comments on why we are responding the way we are.

GAO Recommendations:

The Assistant Administrator of EPA's Office of Air and Radiation, in consultation with state and local agencies, should develop, make public, and implement an asset management framework for consistently sustaining the national ambient air quality monitoring system. Such a framework could be designed for success by considering the key characteristics of effective asset management described in our report such as identifying the resources needed to sustain the monitoring system, using quality data to manage infrastructure risks, and targeting resources toward assets that provide the greatest value. (Recommendation 1)

The Assistant Administrator of EPA's Office of Air and Radiation, in consultation with state and local agencies and other relevant federal agencies, should develop and make public an air quality monitoring modernization plan to better meet the additional information needs of air quality managers, researchers, and the public. Such a plan could address the ongoing challenges in modernizing the national ambient air quality monitoring system by considering leading practices including establishing priorities and roles, assessing risks to success, identifying the resources needed to achieve goals, and measuring and evaluating progress. (Recommendation 2)

EPA Response:

EPA believes the recommendations made by the GAO are useful and, if fully implemented, will add value and help sustain the national ambient air monitoring program. To assure success, we believe it's most important for us to engage our stakeholders in the state, local, and tribal air monitoring agencies. Thus, we generally agree with both of the GAO's recommendations and will work with our state, local and tribal partners to determine the specifics of what will be implemented. We believe that the every-5-year monitoring network assessments required by EPA regulation provide an opportunity for each monitoring agency to design the appropriate changes to their networks, such as those GAO recommended. We believe that any changes would need to be in place and available at least 1 year before the next required 5-year assessment due to EPA Regional offices by July 1, 2025, to help inform that process. As explained in the draft report, the nation's ambient air monitoring program is jointly managed by EPA and state, local, and tribal air agencies. However, almost all infrastructure is owned and operated by the state, local and tribal air agencies; not EPA. Therefore, it would be inappropriate to have new expectations of our state, local, and tribal partners without first working closely with them to define their needs. We will need to work together to determine whether the following existing products available by EPA meet those needs:

- For each National Ambient Air Quality Standard (NAAQS), we produce several documents on the science and policy for each standard, including detailed sections on ambient air monitoring and methods.

- In the National Program Manager Guidance – Monitoring Appendix (https://www.epa.gov/amtic/national-program-manager-npm-guidance-monitoring-appendix), which is updated every 1 to 2 years, we already explain priorities in each monitoring program for each NAAQS pollutant, for air toxics, and for supporting programs, such as the Photochemical Assessment Monitoring Stations (PAMS) and the Chemical Speciation Network (CSN). This document lays out options for investments and divestments that air agencies can consider as they negotiate their State and Tribal Assistance Grants (STAG) with EPA Regional offices. Should we offer additional ways to sustain the network, we would likely build on this product.

- We provide automated assessments of data, where air monitoring agencies can compare the quality of the data from their network to other networks and methods to understand how their data quality compares.

- We are preparing a comprehensive air toxics strategy. This work is under development and includes several elements of air program management, including ambient air monitoring.

The addition of work not covered within already available documentation would come at a cost of staff time and resources, which will spread ambient air monitoring program staff even thinner. Decisions to pursue such work should be made in consultation with our state, local and tribal partners.

In response to Recommendation 1 (concerning establishing an asset management framework), we believe that while much of the information already exists, there is certainly additional information that could be included, as recommended by GAO. We will commit to work with our state, local, and tribal partners on the details not already addressed to ensure they are available, where requested by air monitoring agencies. In addition, since we do not want to provide redundant documentation, we will further commit to enhancing and streamlining, where possible, our existing national products, to align, as appropriate with the GAO's asset management recommendation.

In response to Recommendation 2 (concerning developing a modernization plan), we believe that many elements of a network modernization plan exist in various documents and assessments at the state, local, and tribal level as well as with EPA. However, we recognize that each of these individual elements may not be nationally consistent, publicly available, or readily accessible as a national modernization plan. These include the various documents supporting the NAAQS reviews, the National Program Manager grant guidance, and a series of automated assessments. State, local and tribal agencies already put a great deal of effort into Annual Monitoring Network plans and 5-year assessments. In some cases, the air monitoring agencies already address modernization issues in these documents and, therefore, it would be redundant to set new requirements where not needed. Also, as noted earlier, additional resources are necessary (especially new funding for state, local and tribal air agencies to purchase new equipment) in order to support modernization. We will commit to working with state, local, and tribal air agencies and soliciting their input on improving the availability and national consistency of this information. We will also work to provide that information more clearly in existing documentation or additional documentation, if needed, so that it supports the GAO recommendation. As noted in the draft report, some states have already been successful in modernizing their networks; therefore, we will work to share the successes of those agencies with others. Also, we will continue to explore opportunities for new funding, which is targeted at modernizing the current monitoring network.

Again, I want to thank you and your team for the evaluation of the ambient air monitoring program and for the constructive recommendations. We believe these recommendations will help us, and our state, local and tribal air agency partners, as we work together to improve this national asset. If you have any questions concerning our response, please contact Richard Wayland, Director of the Air Quality Assessment Division in the Office of Air Quality Planning and Standards at (919) 541-4603.

Sincerely,

Anne L. Austin

Anne L. Austin
Principal Deputy Assistant Administrator

Enclosure

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In addition to the individual named above, Joseph Dean Thompson (Assistant Director), Anne Hobson (Analyst-in-Charge), Carolyn S. Blocker, and Reed Van Beveren made key contributions to this report. Also contributing to this report were Kala Amos, Chuck Bausell, Lilia Chaidez, Kendall Childers, Ellen Fried, Cindy Gilbert, Sarah Gilliland, Richard Johnson, John Mingus, Marc Meyer, Patricia Moye, and Sara Sullivan.

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