

Transportation-Related Sources of Nitrous Oxide

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ABSTRACT: Nitrous oxide (N_2O) is a potent greenhouse gas and the most abundant stratospheric ozone-depleting substance. Atmospheric mixing ratios of N_2O have rapidly increased in recent years, and quantifying sources of N_2O emissions is critical for climate change mitigation. We quantified and characterized N_2O emission sources at street level using mobile laboratory measurements in New York City taken over 10 days in January and June 2025. N_2O plume enhancements were strongly correlated with carbon monoxide (CO) and carbon dioxide (CO_2). We identified city buses using *clean air* technology as the source of these enhancements. Using estimates of bus-related CO_2 emissions, we estimated annual N_2O emissions from buses in New York City of $31 (\pm 14)$ tonne- N_2O yr^{-1} . With increased deployment of *clean air* technologies to reduce NO_x pollution from diesel vehicles globally, N_2O emissions from transportation are likely under-reported and should be accounted for in emissions inventories.

KEYWORDS: nitrous oxide, climate, urban, emissions, transportation, mobile sampling, trace gas measurements



INTRODUCTION

Nitrous oxide (N_2O) is a long-lived greenhouse gas with a global warming potential (GWP) that is 273 times that of carbon dioxide (CO_2) over 100 years.¹ With an atmospheric lifetime of over 100 years, N_2O reaches the stratosphere, where it has become the most abundant ozone-depleting substance of the 21st century.² Global mean N_2O mixing ratios have been steadily growing in the troposphere by 1 part per billion by volume (ppbv), reaching 338 ppbv in July 2025.³ For 1980–2020, the largest anthropogenic sources of N_2O were agriculture (3.9 Tg N yr^{-1}) and direct and indirect fossil fuel and industrial sources (3.4 Tg N yr^{-1}).⁴ In recent years, the combustion of fossil fuels for on-road transportation has become a larger fraction of total N_2O emissions globally. Other N_2O sources in urban areas include nitrification or denitrification in wastewater treatment plants (WWTPs)^{5,6} or recreational use.^{7,8}

Various environmental agencies have set stringent regulations on emissions of numerous pollutants (e.g., United States of America (USA) Environmental Protection Agency (EPA), European Emission Standards (EES)) from light-duty (gasoline or diesel) and heavy-duty (diesel) engines. For diesel vehicles, pollutant emissions are often controlled through the use of exhaust after-treatment technologies like Selective Catalytic Reduction (SCR). A common SCR approach uses a 32.5% urea solution in water that is added to the engine exhaust.⁹ While SCR reduces NO_x , it also tends to increase N_2O emissions.^{10,11} A synthesis of studies estimated global N_2O emission rates for the year 2010 by scaling to carbon

dioxide (CO_2) emissions: light-duty vehicles were estimated at $31\text{--}57 \mu\text{g N}_2\text{O/g CO}_2$ ($0.078 \pm 0.023 \text{ Tg N}_2\text{O-N/yr}$) and heavy-duty vehicles at $7\text{--}56 \mu\text{g N}_2\text{O/g CO}_2$ ($0.032 \pm 0.025 \text{ Tg N}_2\text{O-N/yr}$).¹¹

The Volkswagen scandal of 2015 (“Dieselgate”) revealed much greater NO_x emissions from light-duty diesel vehicles than permitted by regulations^{12,13} and resulted in an accelerated adoption of liquid urea-based catalysts in diesel engines for light-duty vehicles in recent years. While these liquid urea-based technologies have been successful in reducing NO_x emissions,¹⁴ they have also resulted in an increase in the emission of other pollutant byproducts, such as ammonia (NH_3).^{14,15}

While some previous experimental studies have investigated N_2O emissions from heavy-duty vehicles with liquid urea-based catalyst technologies,^{16–19} most of these studies have used chassis dynamometer testing, which may not accurately capture real-world emissions. Previous studies have quantified NO_x and other pollutant emissions using a mobile methodology similar to that used here²⁰ to sample real-world vehicle operating conditions in a dense urban environment, including

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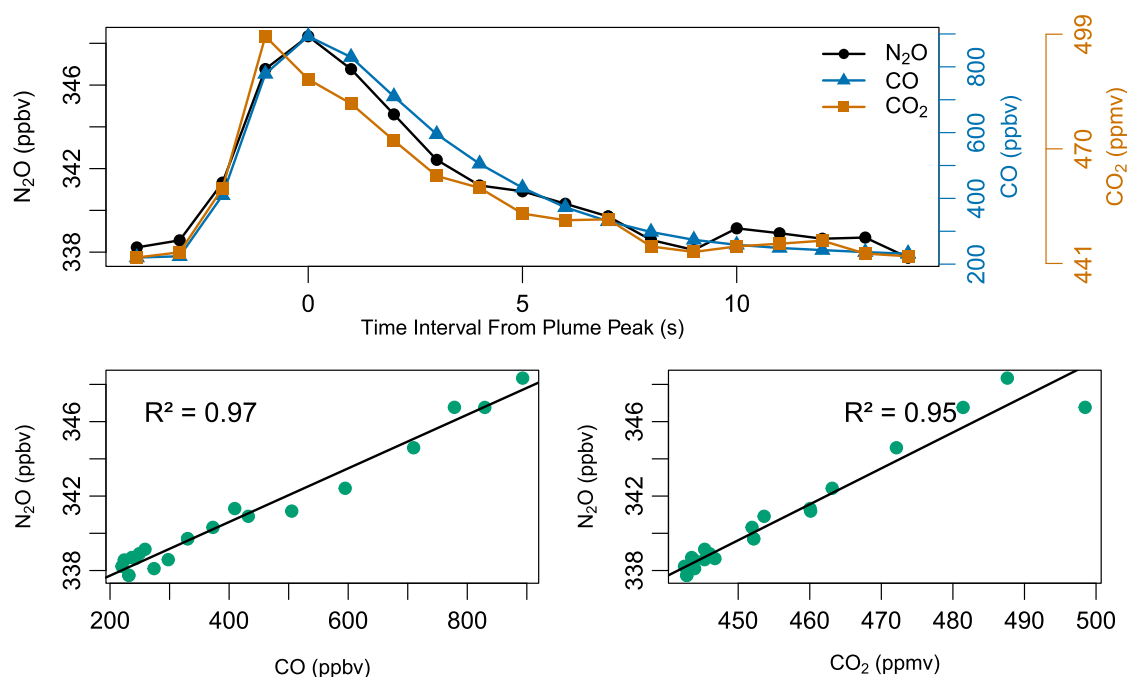


Figure 1. Sample plume extracted from the mobile sampling data. This plume shows a very strong correlation between N₂O and CO ($R^2 = 0.97$) and between N₂O and CO₂ ($R^2 = 0.95$), indicating that a combustion source of N₂O was observed at the street level. Observed on 06/03/2025 at 17:49:00 UTC.

transient driving, stop-and-go traffic, and variable loads. Very few studies have attempted to apply such on-road plume-based methods to quantify N₂O emissions from heavy-duty vehicles.^{21–23} Even fewer such studies have been done in the USA and Europe since the latest EPA standards and Euro 7 standards were adopted for NO_x and particulate matter emissions from heavy-duty engines (adopted in December 2022 for the EPA and April 2024 for Euro 7).^{24,25}

The New York City (NYC) metropolitan area is the most populated metropolitan area in the USA (pop. 20 M), with millions of light- and heavy-duty vehicle trips each day. The Metropolitan Transportation Authority (MTA) operates 5881 buses across NYC (as of January 2022),²⁶ which are a mix of low-sulfur diesel (3779; 64%), electric hybrid diesel (1353; 23%), condensed natural gas (734; 13%), and fully electric (15; 0.3%). 63% of the buses sampled during our study were manufactured after 2013, with only 37% older than 2013.²⁷ These buses comply with the 2010 and later U.S. EPA NO_x standards, which imposed severe restrictions on NO_x emissions from heavy-duty vehicles.^{10,24,28} Most of the MTA buses are part of the New Flyer Xcelsior line, which uses low-sulfur diesel engines and includes SCR with urea as their after-treatment technology for NO_x reduction.^{29,30} In these urea-SCR catalysts, N₂O is formed as a side product of ammonia-NO_x reactions as well as through ammonia oxidation.³¹ The hybrid electric buses use an electric propulsion system that engages when the bus is stopped but use the same low-sulfur diesel engines as the diesel buses. The hybrid and newer diesel buses are labeled as using clean-air technologies. Estimated annual CO₂ emission rates by bus type and number of buses categorized by bus type across the fleet were published by the MTA in 2022.²⁶

Studies from over 20 years ago characterized the particulate³² and NO_x emissions²⁰ from MTA buses. However, no studies have investigated N₂O emissions from NYC-based vehicles, past or present. In our study, we built on

methodology from previous mobile bus²⁰ and natural gas plume detection (e.g., Weller et al., 2018)³³ studies to characterize N₂O emissions from MTA buses that represent 87% of the NYC bus fleet and calculate annual N₂O emissions from the MTA bus fleet.

METHODS

As part of the Transport and Energy Emissions from Manhattan Streets (TEEMS) campaign, we used the New York Atmospheric composition and Air Quality (NYAAQ) mobile laboratory to sample trace gas (N₂O, carbon monoxide (CO), and CO₂) enhancements from diesel and hybrid buses operated by the MTA driving around a high-density neighborhood in NYC. We extracted plumes of CO, a traffic marker, quantified the N₂O/CO₂ ratio for each plume, and calculated the total N₂O emissions by bus type by scaling them with estimates for CO₂ emissions.

Deployment Details

We deployed an Aeris MIRA Ultra N₂O/CO/H₂O, a LI-COR LI-7810 (CO₂/CH₄/H₂O), and a GPS receiver in the NYAAQ Mobile Laboratory. Deployments were conducted over five consecutive days in winter (January 27–31, 2025) and summer (June 2–6, 2025). We sampled the Upper East Side and East Harlem neighborhoods in Manhattan, NYC (72nd–110th Street, 1st–5th Avenue; see Figure S1). The drives were conducted in Manhattan during the day, when bus activity was high, and heavy-duty trucks were relatively uncommon within the neighborhoods sampled. The sampled plumes were visually and temporally associated with identifiable MTA buses, and no other heavy-duty vehicles were consistently present during sampling. According to New York State vehicle registration data,³⁴ around 87% of vehicles registered in 2024 were gasoline-powered and 1.3% were diesel vehicles, suggesting that most of the light-duty vehicles observed on the streets were gasoline-powered. Our mobile laboratory is a light-duty hybrid gasoline vehicle, and when we operated the gasoline engine in an enclosed garage, we saw no enhancements in N₂O despite detecting elevated CO and CO₂ concentrations. This result is consistent with previous literature that indicates that light-duty gasoline vehicles are not a significant source of N₂O.^{35,36} During each drive, we recorded the bus number, bus route, and time of each

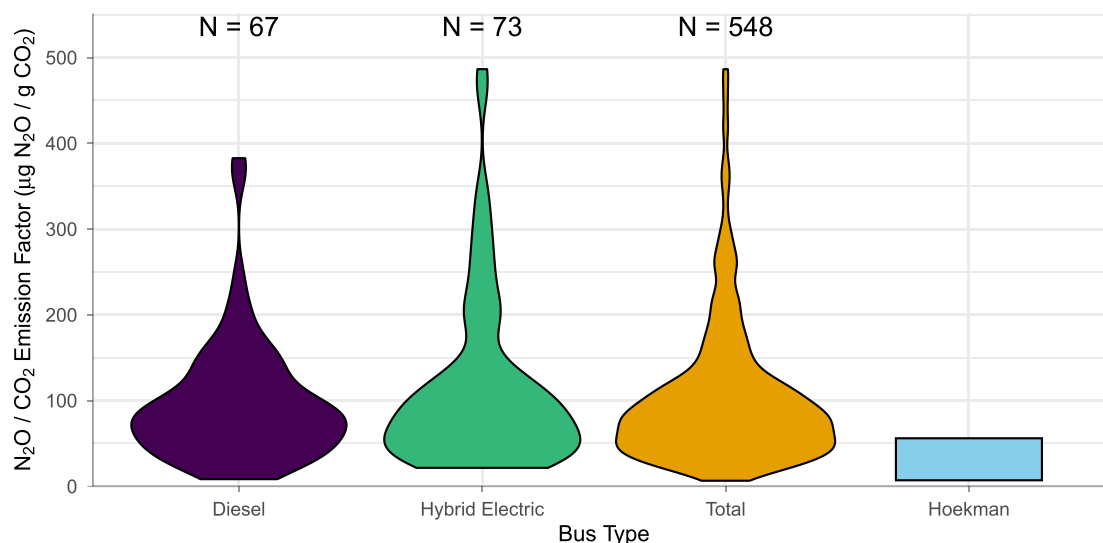


Figure 2. $\text{N}_2\text{O}/\text{CO}_2$ emission factors ($\mu\text{g N}_2\text{O}/\text{g CO}_2$) by bus type from the plumes sampled, compared with the range of $\text{N}_2\text{O}/\text{CO}_2$ emission factors for heavy-duty vehicles from Hoekman (2020).¹¹

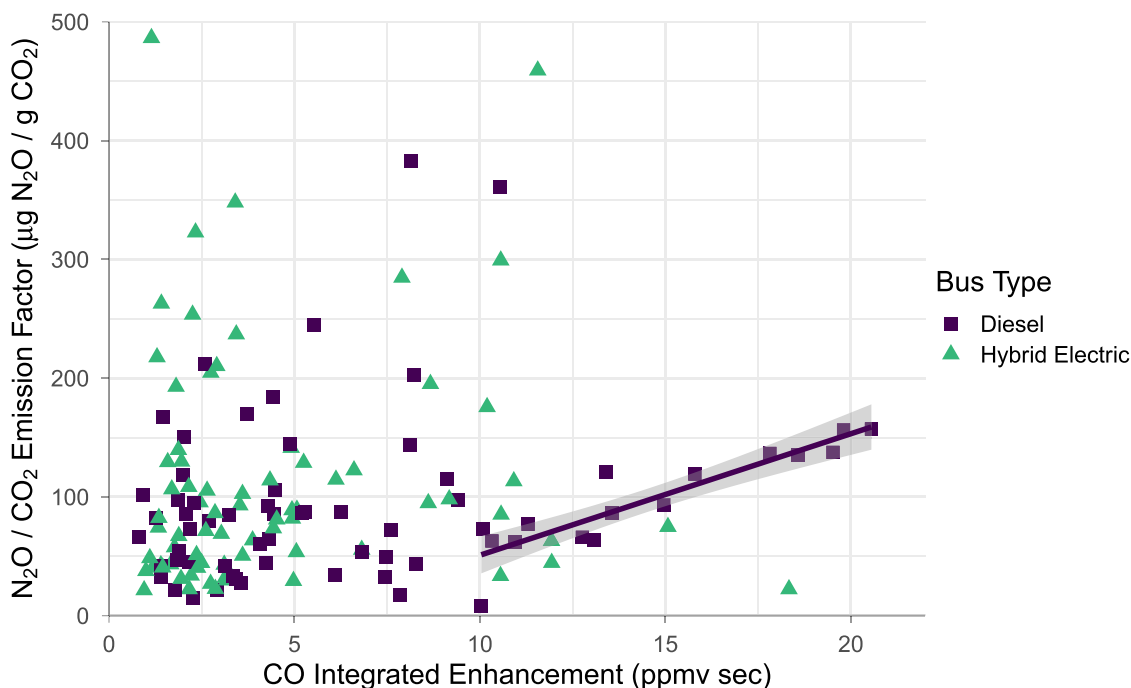


Figure 3. $\text{N}_2\text{O}/\text{CO}_2$ emission factor ($\mu\text{g N}_2\text{O}/\text{g CO}_2$ over the 20 s window) for all the identified CO plumes with an N_2O enhancement ($\Delta\text{N}_2\text{O} > 5$ ppbv) as a function of the CO integrated enhancement: Diesel (purple square), Hybrid Electric (green triangle). Diesel plumes with a CO integrated enhancement greater than 10 ppmv sec were strongly correlated (slope = 10.23 ± 1.27 ; $R^2 = 0.82$).

MTA bus observed near the mobile laboratory, where possible. See Section S1 for more details. The assignment of the bus type to N_2O plumes based on visible buses adds some uncertainty to this analysis.

Plume Extraction, Characterization, and Flux Calculation

Enhancements for each trace gas (ΔX) were calculated as the difference between the observed trace gas mixing ratio and the background: $\Delta X = \text{Observed } X - \text{Background } X$. The background was defined as the median of a 5 min centered running window. Enhancements were clustered together to form plumes if they occurred within 1 s of each other. This interval corresponds to the instrument sampling frequency. In total, we observed 729 plumes with N_2O enhancements greater than 5 ppbv, 627 of which had CO enhancements greater than 50 ppbv (see Figure 1 for an example).

We used a threshold $\Delta\text{N}_2\text{O} > 5$ ppbv to ensure that the identified enhancements were sufficiently above instrument noise and background variability, and therefore represented substantial N_2O enhancements. As the source of some of these N_2O plumes could not be confidently identified, and to ensure we isolated traffic-related emissions, we based our analysis on CO plumes. We identified 2,444 plumes of CO with a peak enhancement above 50 ppbv and found that 548 of these plumes contained N_2O above 5 ppbv. We performed an ordinary least squares (OLS) regression between CO and CO_2 concentrations, and we selected a 20 s window centered on the timing of the maximum CO– CO_2 correlation.

After the plumes were extracted, we calculated the fifth percentile baseline for each trace gas enhancement for each 20 s plume. Defining a separate baseline was especially important for localized changes in

Table 1. Median N₂O/CO₂ Emission Factor, Estimated CO₂ Emissions Per Bus from the 2022 MTA Report²⁶ and Median N₂O Flux Per Bus for That Bus Type^a

Bus type (% of fleet)	Median N ₂ O/CO ₂ emission factor (μg-N ₂ O/g-CO ₂ /bus)	Median N ₂ O/CO ₂ emission factor (mg-N ₂ O/km/bus)	CO ₂ emissions/bus (kg-CO ₂ /bus)	Median N ₂ O flux (kg-N ₂ O/bus/yr)
Diesel (64%)	85.1 [48.1, 120.1]	145.6 [80.6, 205]	7.7 × 10 ⁴	6.6 [3.7, 9.2]
Hybrid (23%)	82.4 [44.5, 129.4]	114.4 [61.9, 180.6]	5.8 × 10 ⁴	4.8 [2.6, 7.5]

^aThe 25th and 75th percentile confidence intervals are shown in square brackets.

the background of CO and CO₂, as there were other large sources of both gases unrelated to buses that were not captured in the enhancements calculated from the 5 min background. For each plume, we calculated the N₂O/CO₂ emission factors and CO integrated enhancements and matched them with identified buses, where possible. We then categorized the N₂O emissions by the type of bus (Figures 2 and 3).

In line with Intergovernmental Panel on Climate Change (IPCC) methodology,³⁷ we assume that N₂O emissions, like CO₂ emissions, scale with fuel use. We multiplied our calculated range of N₂O/CO₂ emission ratios with the reported CO₂ emissions²⁶ to estimate annual N₂O emission rates for a typical bus of each type (expressed as kg-N₂O yr⁻¹). These N₂O fluxes were then scaled by the number of buses in each category to estimate the total annual N₂O emissions from the MTA fleet (see Table 1).

RESULTS AND DISCUSSION

Of the 548 CO plumes with N₂O enhancements, we associated 73 plumes with hybrid electric buses and 67 with diesel buses. We observed N₂O/CO₂ emission factors that were nearly twice the upper range reported in Hoekman (2020)¹¹ (mean observed: 104 μg N₂O/g CO₂ vs Hoekman (2020): 56 μg N₂O/g CO₂). The range of emission factors compiled in Hoekman reflects substantial variability across previous studies, which employed different test platforms and duty cycles for heavy-duty diesel vehicles, including Federal Test Procedure (FTP) transient cycles, extended 16-h duty cycles, and engine dynamometer experiments. N₂O/CO₂ emission factors for hybrid electric and diesel buses were not statistically different from each other, nor were they different from the total plume category, but they had different population distributions (Figure 2) and relationships with CO (Figure 3).

Of the 548 CO plumes with N₂O enhancements, 277 were observed in the winter, and 271 were observed in the summer. The summer and winter plumes showed very comparable N₂O/CO₂ emission factor distributions (Figure S17) and also displayed the same relationship with CO (Figure S18). We confirmed that there was no statistically significant difference between the N₂O/CO₂ emission factors and the CO integrated enhancements for the plumes observed in the summer versus those in the winter (Table S2). Some studies have suggested that cold-weather operation, especially cold starts for vehicles, could lead to larger N₂O emissions.¹¹ However, as we sampled buses midway through their route, they would not be close to a cold start, so we cannot comment on this point.

Hybrid electric buses showed several distinct populations of N₂O/CO₂ emission factors spanning a large range, with a majority below 150 μg N₂O/g CO₂. In general, the hybrid electric buses had a smaller integrated CO enhancement and lower CO/CO₂ ratio than for diesel buses, indicating more efficient combustion. Hybrid electric buses use more efficient propulsion systems, are generally the newer buses within the MTA fleet, and are more likely to incorporate clean air technologies, which could contribute to the larger N₂O and lower CO emissions. Plumes identified as hybrid electric with

CO-integrated enhancements above 12 ppmv sec might have been incorrectly assigned.

Diesel buses generally exhibited lower N₂O/CO₂ emission factors than hybrid buses, with most plumes below 200 μg N₂O/g CO₂. A significant subset of the diesel plumes had large amounts of CO and lower N₂O/CO₂ emission factors. The diesel bus plumes displayed a strong positive correlation between the N₂O/CO₂ emission factors and the integrated CO enhancements above 10 ppmv sec (Figure 3). These high CO plumes likely represent the emissions from older diesel buses lacking the latest clean air technologies. We also observed a small subset of diesel buses that displayed unusually high N₂O/CO₂ emission factors with lower CO integrated enhancements, possibly due to the newest diesel coaches that employ clean air technology or incorrect assignment of bus type (Figure 3).

Using a carbon mass balance approach described in previous plume-based emission factor estimation studies^{21,38} an emission factor can be estimated in units of mg N₂O/km (see Table 1). We assume a carbon mass fraction in diesel fuel of 0.87 (as in Wren et al., 2018)³⁸ and a mileage of 3.7 miles per gallon for diesel buses and 4.5 miles per gallon for hybrid electric buses (obtained from a 2022 MTA report)²⁶ for this calculation. Most previous studies^{16,17} have used chassis dynamometer testing methods that include high emissions observed under cold-start conditions. Our study sampled buses under real-world driving conditions without cold starts, but we observed N₂O emissions within the range of those reported in earlier studies (see Table S1).

Overall, we sampled bus types that represent 87% of the buses across the MTA fleet.²⁶ We multiplied the annual CO₂ emissions estimated for each bus type²⁶ with the 50% Confidence Interval (C.I.) of the N₂O/CO₂ emission factors to calculate the corresponding N₂O flux for each bus type (Table 1). We then calculated the median annual N₂O flux from the MTA bus fleet as 31 (±14) tonnes-N₂O yr⁻¹.

WIDER CONTEXT

The EDGAR N₂O inventory estimated 212 tonnes of N₂O emissions from on-road vehicle transportation from NYC for 2023.³⁹ Our results suggest that N₂O emissions from the less than 6000 MTA buses alone could contribute 9–21% of the on-road N₂O emissions. With more than an estimated 125 000 trucks moving into and out of NYC on a given day,⁴⁰ our results imply that the total N₂O emissions from on-road transportation in NYC are likely to be vastly underestimated.

In response to the Dieselgate scandal,^{12,13} most light-duty diesel vehicles in Europe sold since 2018 are now equipped with liquid-based urea catalysts, which have led to an increase in ammonia emissions.¹⁴ Our results suggest that there may also have been a corresponding but previously unmeasured increase in N₂O emissions from on-road transportation. However, measurements of ammonia alongside N₂O are needed to confirm whether the observed N₂O enhancements

originate from the SCR systems of these vehicles. Future research on on-road transportation in Europe should investigate the N₂O emissions. Additionally, future studies, ideally conducted in partnership with a transport authority or bus manufacturer, are needed to characterize N₂O emissions as a function of vehicle age and exhaust aftertreatment configuration. Our results suggest that there is a need to consider the climate impacts of the adoption of clean-air technologies.

■ ASSOCIATED CONTENT

Data Availability Statement

Data are available at Data Dryad at DOI:10.5061/dryad.sxksn03h4.

■ Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acsestair.6c00271>.

Details of the mobile lab deployment, figures showing the route driven each day, additional details about plume characterization, and an analysis of summer versus winter plume analysis (PDF)

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Notes

The authors declare no competing financial interest.

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