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# Updated Conceptual Model of Ozone Formation in the Cleveland, OH Area

## Technical Report

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# Updated conceptual model of ozone formation in the Cleveland area

This document updates the conceptual model of ozone formation in the Cleveland area prepared by LADCO in 2023 as part of the report: "Conceptual Models of Ozone Formation in the Great Lakes Region: Technical Report" (LADCO, 2023). The current report includes data through 2024 or 2025, as available, and updates the discussion accordingly. It also refers to more extensive analyses and figures in the original report where appropriate.

The Cleveland area encompasses 7 counties in northeastern Ohio. The area is currently designated serious nonattainment for the 2015 $O_3$ NAAQS (89 FR 101901).

## Meteorology and Transport

The primary meteorological factors driving $O_3$ formation throughout the Cleveland area were the maximum temperature during the day or afternoon and the midday dew point or relative humidity (Figure 2.2 in LADCO 2023). This finding was based on independent analyses by the U.S. EPA using a generalized linear model (GLM) and by LADCO using a classification and regression tree (CART) analysis. The Cleveland area is primarily impacted by stagnation-driven $O_3$ events (e.g., Figure 2.3 in LADCO, 2023), although lake breezes also influence $O_3$. Dry tropical synoptic weather systems are the most important on $O_3$ episode days; moist tropical and dry moderate synoptic systems are also associated with high $O_3$ in this region (Figure 2.5 in LADCO, 2023).

Lake breezes play a role on some $O_3$ episode days in the Cleveland area. Lake breezes arrive from either the west-northwest or the north to northeast (Figure 2.11 in LADCO, 2023). Unlike in the Lake Michigan area, many $O_3$ episodes are driven by synoptic winds rather than by lake breezes. On these days, the synoptic winds may come from the southwest, the west, or the northwest (see Section 2.1.3 in LADCO, 2023).

HYSPLIT back-trajectories model that winds reaching Cleveland's Eastlake monitor on high-$O_3$ days generally came from over land to the southwest (Figure 2.17 in LADCO, 2023).

On several days, $O_3$-rich air arrived from over the lake to the west or northwest. Monitored winds at the nearby Cleveland Burke Lakefront airport during high-$O_3$ hours at the Eastlake monitor primarily arrived from over the lake to the west-northwest to north. These discrepancies may have resulted because the coarse grid cells used for the HYSPLIT modeling make it difficult for the model to capture lake breeze impacts. The differences may also reflect the different locations of the wind monitoring (at the airport) and the HYSPLIT endpoints (at the Eastlake monitor); these different locations may be impacted by winds from different directions. The incremental probability analysis suggests that transport to Cleveland monitors comes from the Cleveland area and areas farther south (Figure 2.18 in LADCO, 2023). Source apportionment modeling supports this conclusion, finding that Ohio sources were the largest contributors to high $O_3$ in this area, with the contributions from the Cleveland area being about half as large as the contributions from other parts of Ohio (Figure 1). Overall, the modeling suggests that emissions from Cleveland and nearby areas are the greatest contributors to high $O_3$ at the Cleveland monitors. These results confirm the importance of stagnation events, which allow local emissions to build up to high levels, in this area. The ground-based monitoring suggests that transport from over the lake may also be important.

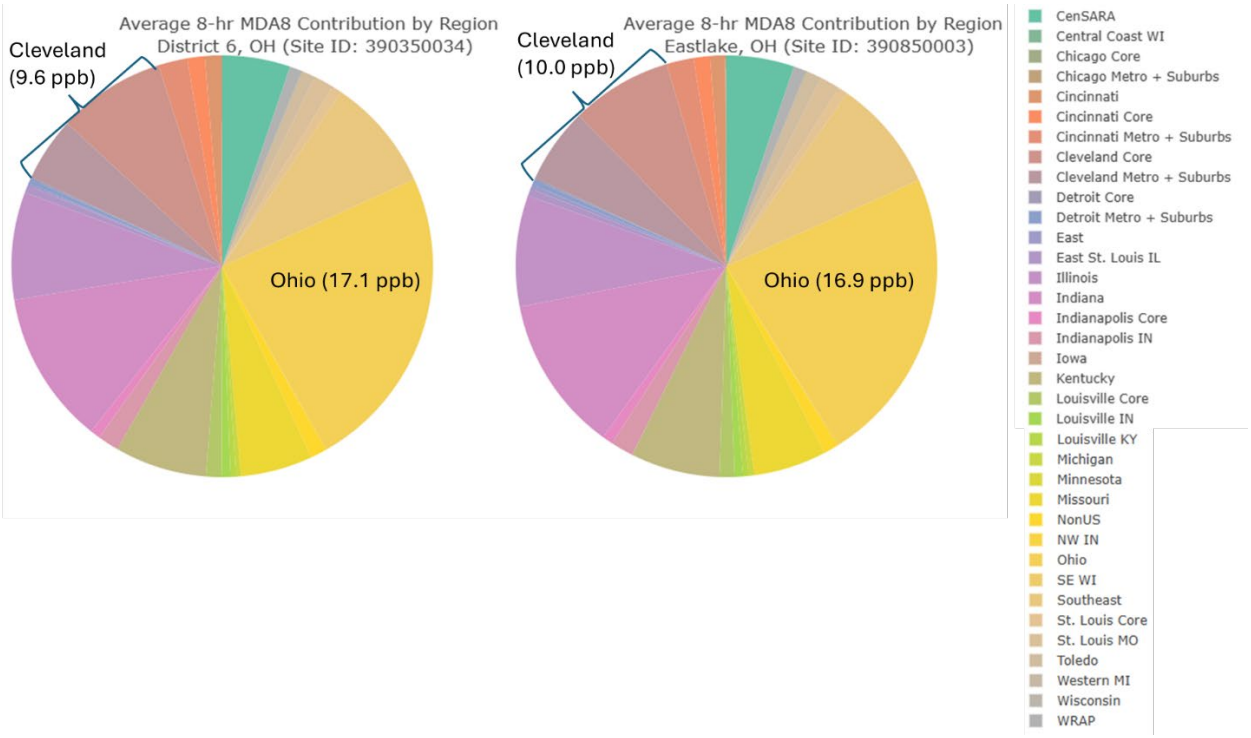


**Figure 1. Source apportionment modeling results for high-$O_3$ days at the (left) District 6 and (right) Eastlake monitors in Cleveland.[1] Cincinnati contributed 3.5 ppb at District 6 and 3.3 ppb at Eastlake.**

## Ozone precursor emission and concentration trends

Emissions of the $O_3$ precursors NOx and VOCs have decreased dramatically from Ohio and neighboring states. From 1990 to 2024, NOx emissions from Ohio sources decreased by 84% (Figure 2.20), and VOC emissions decreased by 70% (Figure 2). Emissions of NOx and anthropogenic VOCs for Ohio were concentrated in the urban areas, with the greatest emissions from the largest cities (Cleveland, Columbus, and Cincinnati-Dayton; Figure 2.23 in LADCO, 2023). Biogenic VOC emissions were fairly low in the Cleveland area, with greater emissions from the forested areas to the south (Figure 2.23 in LADCO, 2023). Emissions of both NOx and VOCs are projected to continue to decrease in Ohio through at

[1] Figures are from the LADCO CAMx 2022 Daily APCA Ozone Tracer Contributions app (https://ladco.shinyapps.io/LADCO_CAMx2022_APCA-Map_Dashboard/) and exclude contributions from intercontinental and boundary conditions (ICBC). Contributions are shown for days with MDA8 > 70 ppb.

least 2028, although at slower rates than in the past (Figure 2.24 and Figure 2.25 in LADCO, 2023).

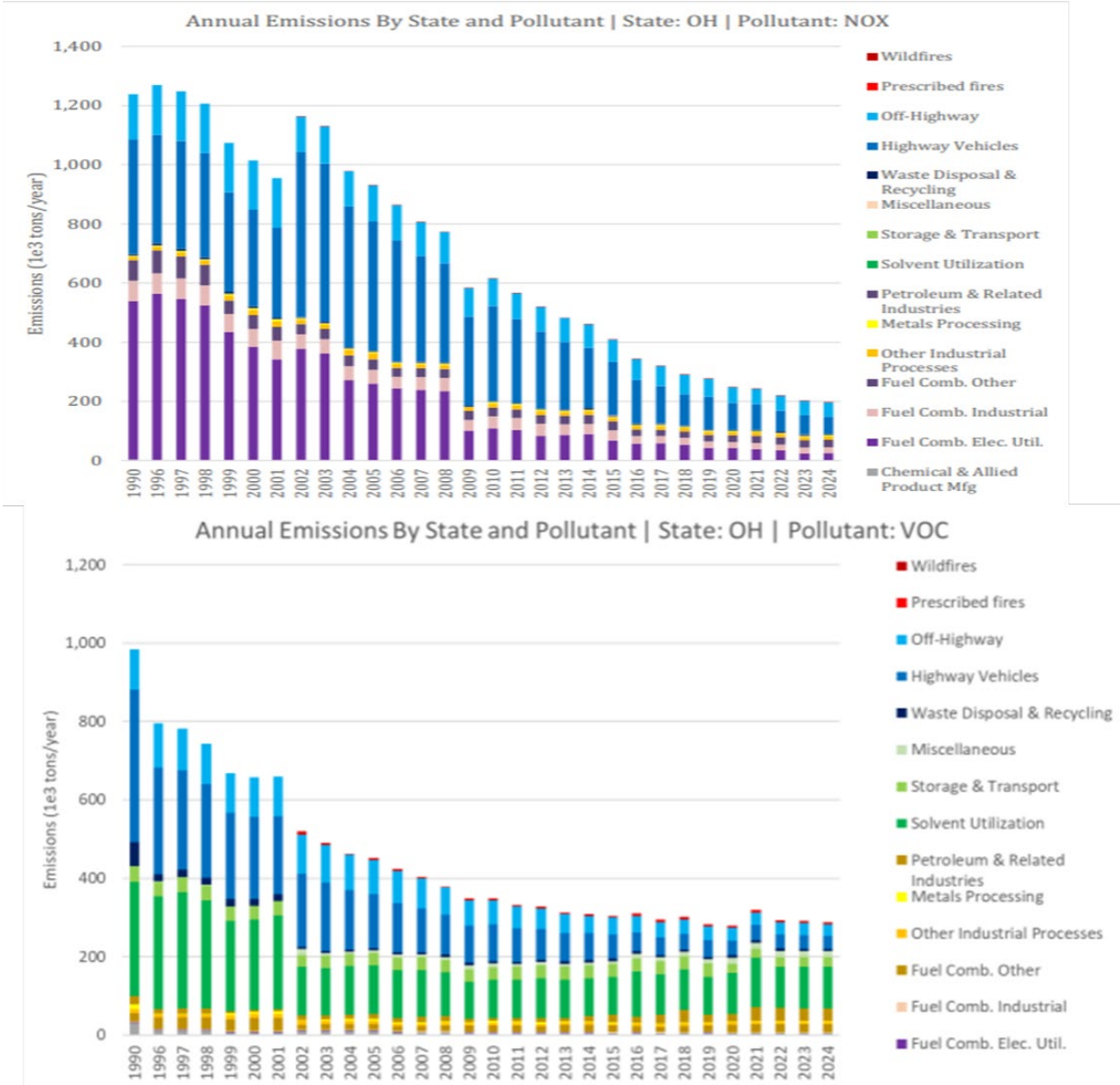


**Figure 2. Ohio statewide (top) NOx and (bottom) VOC emissions trends (1000 tons/year) by emissions sector. From LADCO (2026).**

Monitored concentrations of $O_3$ precursors have also generally decreased over the last few decades in Cleveland (Figure 3). Monitored $NO_2$ concentrations decreased most years

from 1995 to a minimum during the pandemic in 2020 at the GT Craig monitor (390350060). The Cleveland Near Road site (390350073) had a minimum in 2022. $NO_2$ concentrations appear to have increased since these minimum values. These trends in monitored $NO_2$ concentrations agree relatively well with the changes in emissions of NOx. Trends in anthropogenic hydrocarbons[2] are less clear than those of $NO_2$, in part because no monitors have complete long-term records and the monitors haven't measured a consistent suite of compounds. The measured anthropogenic hydrocarbons decreased in concentration at three monitors from the early to late 2000s to the early 2010s, and concentrations decreased slightly at two monitors from the late 2010s to the early 2020s (Figure 3). However, given the patchy record, it is hard to draw conclusions about hydrocarbon trends in this area. Unfortunately, there are no long-term records of the biogenic hydrocarbon isoprene or of carbonyls in this area.

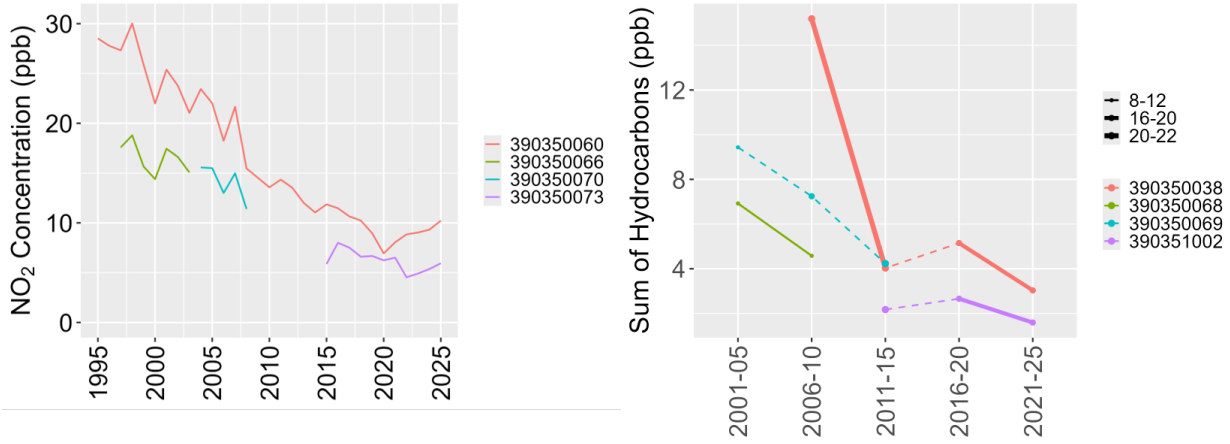


**Figure 3. Timeseries of mean summertime (left) $NO_2$ and (right) hydrocarbons (excluding isoprene) at monitors in the Cleveland nonattainment area. Values are the annual mean of daily mean values for $NO_2$ and the 5-year mean of daily mean values for VOCs, in ppb. Only monitors that operated at least five years are shown. For the hydrocarbons, the thickness of the lines and points indicates the number of**

[2] We averaged the hydrocarbon concentrations together over a 5-year period to account for the sparsity of data caused by the sporadic sampling (generally only 1 in 6 days during June through August). Note also that different monitors measured different numbers of compounds, making it harder to compare between monitors and sometimes between years.

**compounds measured in that set of years; dashed lines connect points with different numbers of compounds.**

## Ozone formation chemistry

$O_3$ formation in the Cleveland area appears to have be primarily NOx-sensitive with transitional chemistry in downtown Cleveland and to the northeast along the lakeshore (Table 2.1 in LADCO, 2023). This means that $O_3$ concentrations will respond best to reductions in NOx emissions, but combined NOx and VOC emissions reductions will be most effective in the downtown and lakeshore areas. The chemistry in this area appears to be shifting away from VOC-sensitive chemistry towards more NOx-sensitive chemistry, meaning that NOx emissions reductions will become even more effective in the future.

## Trends in ozone concentrations

The highest $O_3$ concentrations in the Cleveland nonattainment area have consistently been at monitors to the northeast of downtown along the lakeshore, with the highest concentrations generally at the Eastlake monitor (Figure 1.2 in LADCO, 2023). $O_3$ design values at the peak monitors decreased from at least the mid-2000s through the mid-2010s and have decreased more slowly since then (Figure 4). The spread in monitored concentrations has remained wide over time. Relatedly, the design values at the lowest-concentration monitors have been roughly steady since the mid-2010s. A separate analysis by LADCO shows that $O_3$ on $O_3$-conducive days has generally been decreasing (Figure 5; LADCO, 2025).

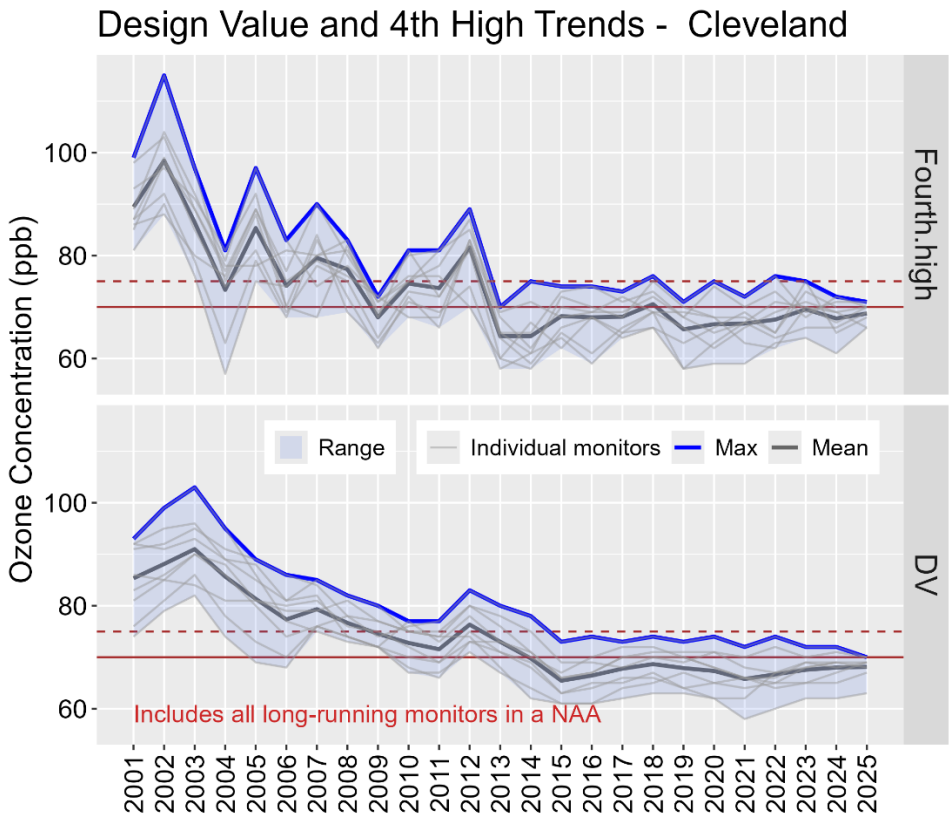


**Figure 4. Trends in (top) annual fourth high daily maximum 8-hour (MDA8) $O_3$ concentrations and (bottom) $O_3$ design values at all long-running monitors in the Cleveland nonattainment area. Pale gray lines are the values at individual monitors, the dark gray line shows the mean value, and the blue line shows the maximum value in the area. Long-running monitors are monitors that operated at least 14 years between 2005 and 2022. 2022 data are preliminary. $O_3$ design values are the three-year average of the fourth-high MDA8 values.**

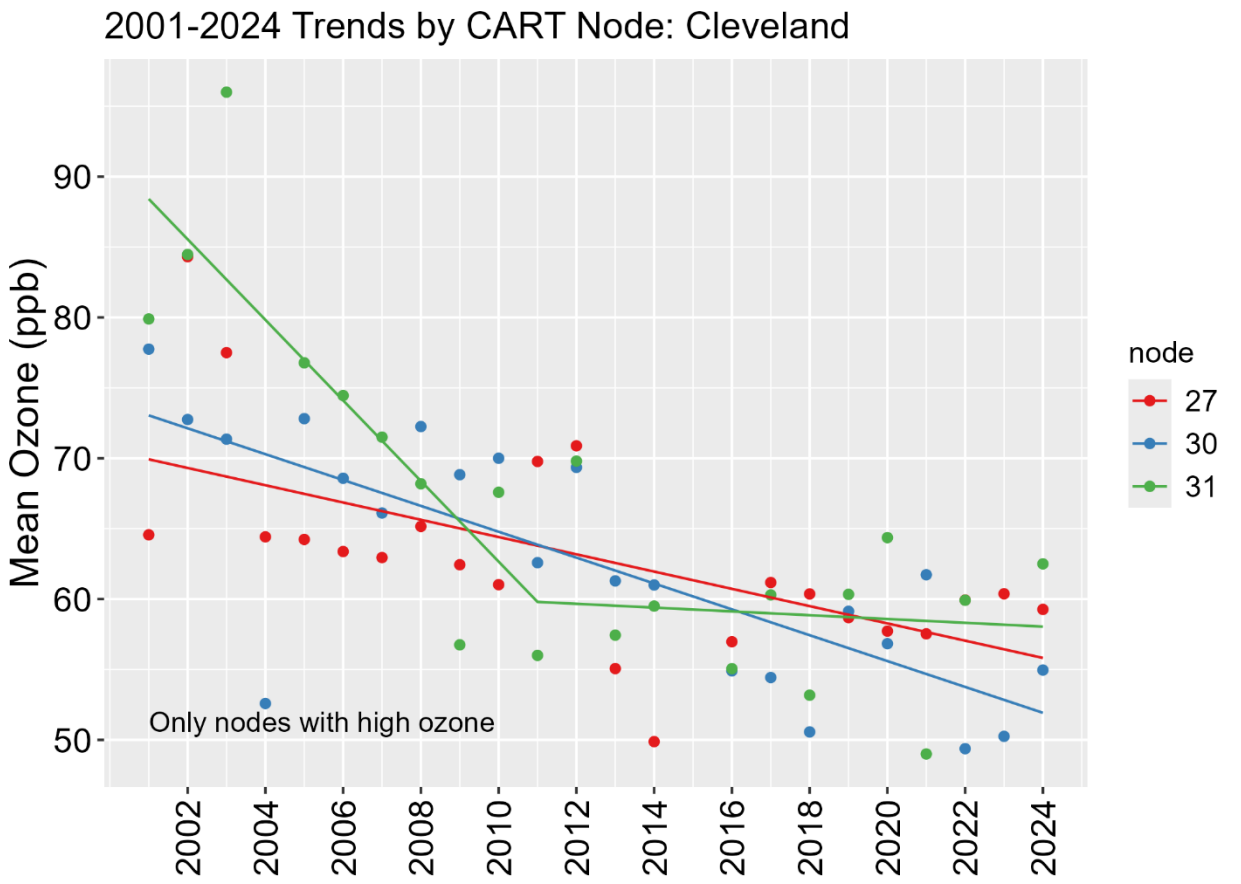


**Figure 5. Trends in average (mean) $O_3$ in high-$O_3$ nodes for monitors in the Cleveland nonattainment area. Nodes are groups of days with similar meteorology, and high-$O_3$ nodes are those with mean $O_3$ concentrations over 50 ppb. See LADCO (2025) for more details on the methodology.**

## Origins of ozone trends

Overall, annual $O_3$ concentrations are strongly impacted by that year's meteorology, particularly by the occurrence of hot temperatures and low dew points and relative humidity. However, the long-term $O_3$ trends result primarily from changes in $O_3$ precursor emissions and concentrations, as mediated by the local $O_3$ formation chemistry regime. Since the area has NOx-sensitive or transitional chemistry, $O_3$ concentrations decreased primarily in response to reductions in NOx emissions, although the VOC emissions reductions have likely also contributed. However, it is harder to explain the very slow rate of reductions in $O_3$ design values since the mid-2010s given that we believe that both NOx

and VOC emissions decreased during this time, albeit more slowly than previously. This trend could result from changes in meteorology, either due to natural variability or to climate change. Increasing temperatures or changes in other meteorological parameters could increase the number and severity of $O_3$-conducive days. Given the NOx-sensitive or transitional chemistry and the projected continued reductions in NOx emissions, we would anticipate that $O_3$ concentrations and design values in the Cleveland area should continue to decrease in the future. However, if the flattening out of $O_3$ design values is due to climate change, this factor may counter the anticipated reductions due to emissions reductions.


**References**

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