Evaluating the Impact of the U.S. EPA’s Proposed Revisions to the SO_2, NO_2, and O_3 Primary Standards on the U.S. Aviation Sector

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Abstract

This work examined the effects of aviation emissions in causing locations in the continental United States to potentially exceed recently-proposed standards for three EPA criteria pollutants. The impact of aircraft on NO_2, SO_2, and O_3 concentrations was evaluated in 2005 and 2025 using CMAQ. It was found that aviation is not an important contributor to SO_2 exceedances. Aviation is an important NO_2 contributor in certain urban areas, and it has varied effects on ozone (positive or negative) in urban areas. Aircraft will contribute more to NO_2 and O_3 exceedances in 2025 than in 2005.

1. Introduction

Under the Clean Air Act, the U.S. EPA is required to set primary and secondary standards for pollutants which are harmful to human health, visibility, ecosystems, crops, and buildings. Primary standards protect public health, while secondary standards aim to achieve other public welfare objectives. Collectively, these standards are referred to as National Ambient Air Quality Standards, or NAAQS.

The EPA has recently proposed changes to the primary standards for SO_2, NO_2, and O_3.[1, 2, 3] These changes are summarized in Table 1. Under the proposed rules, a county which violates the annual average NO_2 standard once or which violates any of the other proposed standards four times in a year (averaged over a three-year period) is in non-attainment of the relevant standard is required to take action to come into compliance.

It is important to investigate whether the proposed changes to the NAAQS would have an impact on the aviation sector. If it is found that aircraft are an important source of SO_2, NO_2, or O_3 in an area which is likely to be in non-attainment under the proposed standards, then a reduction in aircraft emissions of the relevant pollutant may be required in that area. Research results demonstrating this impact may provide airport and aircraft operators additional time to determine the best ways to reduce emissions without adversely affecting transportation or economic objectives. On the other hand, if it is found that aircraft are not an important source of a criteria pollutant in a non-attainment area, results to this effect may help policymakers focus their attention on controlling other emissions sources which have a greater impact on pollutant concentrations.

Pollutant	**Current Standard (Primary)**	**Proposed Standard (Primary)**
SO_2	140 ppb (24-hour avg)	50 - 150 ppb* (1-hour avg)
	30 ppb (annual avg)	
NO_2	53 ppb (annual avg)	53 ppb (annual avg)
		65-150 ppb** (1-hour avg)
O_3	75 ppb (8-hour daily max)	60 - 70 ppb (8-hour daily max)
* 50 - 150 ppb is the complete range of possible SO2 standards on which the EPA is taking comments. The EPA is currently proposing that the standard fall in the 50 - 100 ppb range.		
** 65 - 150 ppb is the complete range of possible standards on which the EPA is taking comments. The EPA is currently proposing that the standard fall in the 80 - 100 ppb range.		

Table 1: Proposed changes to NAAQS primary standards.

The objective of this research was to understand the impact of aviation emissions on the number and severity of instances in which sulfur dioxide, nitrogen dioxide, and ozone concentrations would exceed the proposed NAAQS. In order to achieve this objective, I analyzed the results of four air quality simulations produced by version 4.6 of the Community Multiscale Air Quality Modeling System, or CMAQ. As the proposed standards take the form of ranges (from which the EPA will select final values), the impact of aircraft on each pollutant was investigated across the entire range of possible standards in all parts of the continental United States. The years 2005 and 2025 were each modeled via two simulations: one which included and one which omitted aircraft emissions. In addition, the model's precision and error were estimated for the year 2005 by comparison with surface-based monitor data.

2. Methodology

Pollutant concentrations were estimated using CMAQ, an Eulerian atmospheric model which uses emissions and environmental inputs in a chemistry-transport model to predict species concentrations in each grid cell at each time step during the model run.[4] CMAQ can be configured for particular research tasks so as to balance data richness with computational requirements (simulation runtime). For this research, a 36-km modeling domain covering the continental United States, the upper portion of Mexico, and the lower portion of Canada was used. Boundary conditions for this domain were extracted from the GEOS-Chem modeling system (see model description by Bey et al.[5]). Meteorology data were produced by the MM5 modeling system. Pollutant concentration data were generated for each hour of the year, or 8,760 hours for each simulation.

Four simulations, or testcases, were completed. For the year 2005, one testcase estimated pollutant concentrations from all sources except aircraft, while the other testcase included aircraft emissions from 99 major U.S. airports. Two similar testcases were completed for the year 2025. Non-aviation emissions were based on the EPA's National Emissions Inventories. (Future year projection inventories for 2020 and 2030 were interpolated to obtain 2025 values.) Aircraft emissions were based on estimates from the Next Generation Air Transportation System's Joint Planning and Development Office (NextGen JPDO). Only emissions during landing and take-off cycles (up to 10,000 feet in altitude) were included. Between 2005 and 2025, it was estimated that there would be a reduction in non-aircraft SO_2 and NO_2 emissions (corresponding to stricter regulation and improved pollution control technologies) and an increase in aircraft emissions (corresponding to an increase in air travel demand). As a result, from 2005 - 2025, aircraft NO_2 emissions were projected to rise from 0.43% to 1.40% of total NO_2 emissions, and aircraft SO_2 emissions were projected to rise from 0.04% to 0.15% of total SO_2 emissions. (O_3 is not emitted directly. It is formed via chemical reactions in the atmosphere.)

The model results for 2005 were compared with surface monitor data using the Atmospheric Model Evaluation Tool, or AMET. The CMAQ model runs and AMET comparison were performed by Matt Woody, a fellow graduate student at the University of North Carolina at Chapel Hill.

Although parts of Mexico and Canada were included in the simulation, my analysis focuses on the continental 48 United States. There are two reasons for this choice. First, Canada and Mexico are not subject to EPA standards. Second, robust predictions of changes in emissions by 2025 in Canada and Mexico were not available, limiting the accuracy of 2025 data in those areas.

3. Results and Analysis

3.1 Model Performance

In Figure 1, the model results show less than 15% bias relative to monitor observations for all three chemicals. SO_2 and O_3 were slightly over-predicted by the model, while NO_2 was slightly under-predicted. There is one unusual aspect of the SO_2 data: AMET analysis indicates the CMAQ model is biased high because the density of points above the 1:1 centerline in Figure 2 is very great. However, there exist some high observations which are not reflected in the model results, and they are masked (in Figure 1) by the fact that the model is biased high for non-exceptional exceedances. No such unusual behavior occurs for NO_2 or O_3, so no scatterplots for these pollutants are provided.

These findings regarding SO_2 are similar to those of Marmur et. al.,[6] who also conducted a CMAQ simulation using a 36-km grid. They note that "urban SO_2 concentrations are underpredicted due to artificial dilution of emissions sources in the coarse grid. Rural sites exhibit a slight overprediction of SO_2 concentrations." Figure 1 is an analysis of the entire domain, which mostly consists of rural cells. Hence, we see the same overprediction as Marmur et al. In this study, the very high-concentration SO_2 observations (in Figure 2) probably do not occur in urban areas (see Table 5), but nevertheless, the explanation for the failure of the model is likely the same: major SO_2 sources are diluted by the 36-km grid size, resulting in substantial CMAQ underprediction for those particular events.

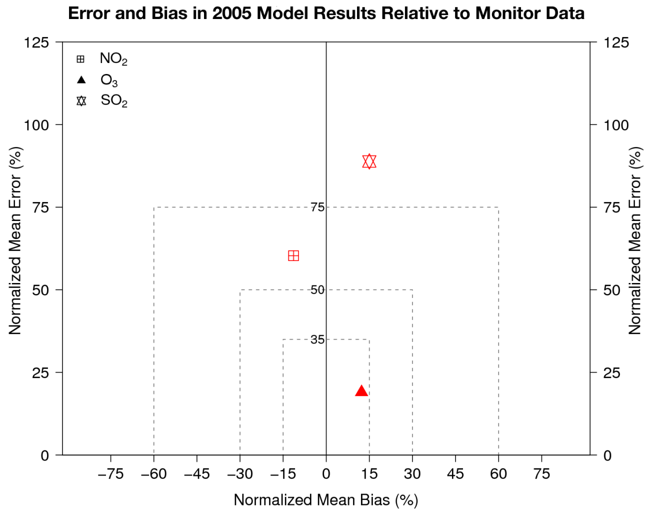

Figure 1: Error and Bias in 2005 Model Results Relative to Monitor Data. These statistics are found by pairing hourly monitor observations with model predictions and finding average error and bias (across the U.S.).

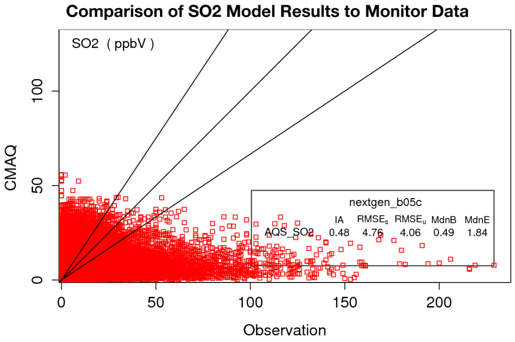

Figure 2: Comparison of 2005 SO_2 model results to monitor data. Each point is a single hourly observation in a grid cell containing a surface monitor. All hours and all monitors are included, except for a few instances in which a monitor failed to record an observation.

3.2 Sulfur Dioxide

Table 2, a **summary statistics** table, notes the number of exceedance events in each year and how many of those exceedances did not occur in testcases without aircraft emissions. In addition, the table includes the fraction of average pollutant concentration attributable to aircraft across the entire domain in all timesteps, and that same metric but including only exceedance events. For purposes of this paper, an “exceedance event” is defined as a one-hour time period in a single grid cell where pollutant concentration exceeds the lowest concentration considered by the EPA, in Table 1. Therefore, a county which experiences three or fewer exceedance events every year would not be in non-attainment, as the EPA considers the fourth-highest 1-hour maximum concentrations when making this determination. In the case of SO_2, Table 2 illustrates that aircraft contribution to exceedance events was more than an order of magnitude smaller than aircraft contribution to total SO_2 concentration.

Statistic	**2005**	**2025**
Number of Exceedance Events (based on 50 ppbv std.)	62 events	43 events
Exceedances due to Aircraft	0 events (0%)	0 events (0%)
Fraction of Annual Average [SO_2] due to Aircraft	0.05%	0.14%
Fraction of Exceedance Event [SO_2] due to Aircraft	0.004%	0.001%

Table 2: Summary statistics for SO_2

Tables 3 and 4 are **exceedances by location** tables. They provide detailed information about those grid cells which experienced the greatest number of exceedance events based on model results. In these tables, the “Avg Aircraft Contrib” column shows the average increase or decrease in pollutant concentration during exceedance events due to the presence of aircraft. The "% Aircraft Contrib" column expresses this value as a percentage of the average pollutant concentration during exceedance events. In Table 3, it can be seen that during 2005, only 15 SO_2 exceedances occurred inside the United States, all of which fell in the 50 - 57 ppbv range. By 2025, there will only be one U.S. cell in exceedance with a maximum value of 51 ppbv (Table 4).

# Excd	row	col	Location	Avg Excd	Max Excd	Avg Aircraft Contrib	% Aircraft Contrib
8	68	107	Detroit, MI	54.82 ppbv	56.23 ppbv	0.001 ppbv	0.00%
4	22	114	Tampa, FL	54.13 ppbv	55.72 ppbv	0.029 ppbv	0.05%
1	95	138	Washington County, OH	50.22 ppbv	50.22 ppbv	0.000 ppbv	0.00%
1	59	115	Morgantown, VW	50.55 ppbv	50.55 ppbv	0.003 ppbv	0.01%
1	61	113	Brooke County, WV	52.17 ppbv	52.17 ppbv	0.002 ppbv	0.00%
Note: The remaining 47 exceedances were located in Canada, primarily near Thompson, MB.							

Table 3: 2005 SO_2 Exceedances by Location (U.S. only, complete with 5 cells)

# Excd	row	col	Location	Avg Excd	Max Excd	Avg Aircraft Contrib	% Aircraft Contrib
6	68	107	Detroit, MI	50.68 ppbv	51.04 ppbv	0.003 ppbv	0.01%
Note: the remaining 37 exceedances were located near Thompson, MB, Canada.							

Table 4: 2025 SO_2 Exceedances by Location (U.S. only, complete with one cell)

Figure 3 is a map of **aircraft contribution to average pollutant concentration**. A map of this metric is included for each pollutant and provides a sense of where in the country aircraft effects are most important. Maps depicting NO_2 and O_3 **exceedance events** are also included in those pollutants' sections. (There were too few SO_2 exceedances for such a map to be helpful.) Figure 3 shows that aircraft contribution to SO_2 is greatest in urban areas, particularly in the eastern half of the U.S. Frequently-used flight corridors of short length (such as Las Vegas, NV to Los Angeles, CA) are visible.

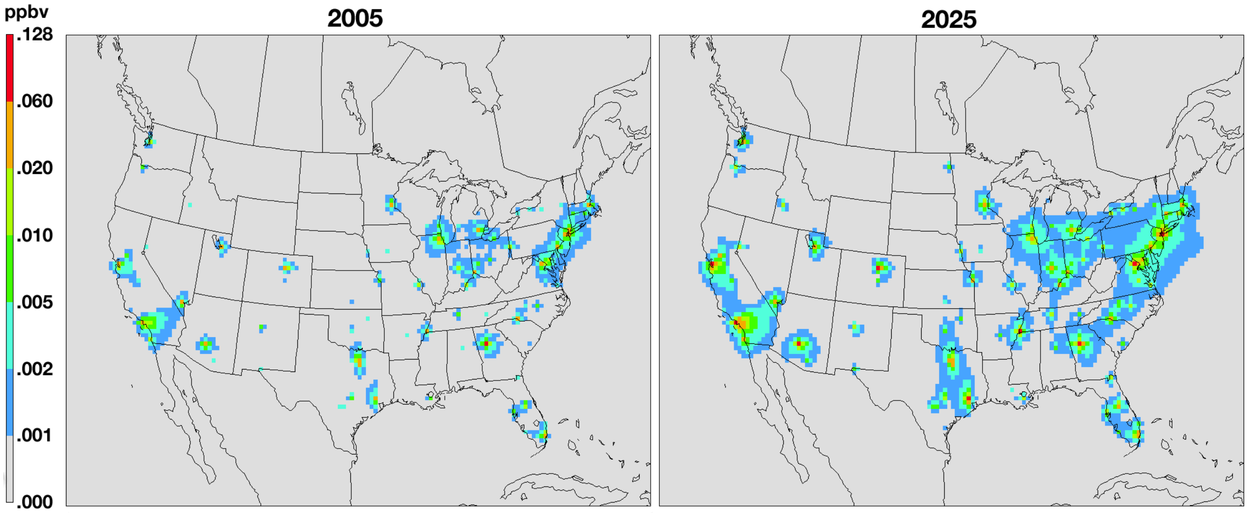

Figure 3: Aircraft Contribution to Annual Average SO_2 Concentration in 2005 and 2025 (ppbv)

Table 5 shows **aircraft contribution to maximum pollutant concentrations in counties with the highest exceedances**. This table shows the effects of aircraft on the highest 1-hour modeled concentrations in the five counties with the highest pollutant concentration as measured by EPA's monitor network (taking the 3-year average of 4th-highest concentrations for 2006-2008). This table provides data about the role of aircraft in areas which are known to be in non-attainment from monitor data, irrespective of whether the model found any exceedances in those areas. (Each county is represented via the most accurately-located grid cell. When several grid cells are located within a county, the grid cell with the greatest contribution due to aircraft, whether positive or negative, is used. This is to ensure important aircraft effects within a county are not overlooked.)

The counties with SO_2 exceedances of the greatest magnitude, listed in Table 5, are rural counties. The higher percentage contribution of aircraft in Gila, AZ occurs because the model predicted a maximum SO_2 concentration under 4 ppbv in both 2005 and 2025. The fact that this prediction is an order of magnitude lower than the model predictions for the other four counties (despite their similar 2006-2008 monitor values) makes the results for Gila, AZ suspect. The percentage contributions of aircraft in the other four counties are in line with the average percentage contribution of aircraft across the domain but exceed the percentage contribution of aircraft to exceedance events predicted by the model (see Table 2).

County	Monitor Value	2005 Max Conc	2005 Aircraft Contrib	2025 Max Conc	2025 Aircraft Contrib
Jefferson, MO	372 ppbv	27.87 ppbv	0.01 ppbv (0.04%)	14.19 ppbv	0.03 ppbv (0.21%)
La Salle, IL	307 ppbv	22.04 ppbv	0.01 ppbv (0.05%)	16.66 ppbv	0.02 ppbv (0.12%)
Gila, AZ	273 ppbv	3.60 ppbv	0.01 ppbv (0.28%)	3.63 ppbv	0.01 ppbv (0.28%)
Morgan, OH	262 ppbv	30.68 ppbv	0.01 ppbv (0.03%)	12.08 ppbv	0.00 ppbv (0.00%)
Tazewell, IL	238 ppbv	25.15 ppbv	0.00 ppbv (0.00%)	16.20 ppbv	0.00 ppbv (0.00%)

Table 5: Aircraft Contribution to Maximum SO_2 Concentrations in Counties with Highest Exceedances based on Measurements

The CMAQ model predicted few SO_2 exceedance events in the United States (15 in 2005, 6 in 2025). Those SO_2 events which were predicted fell in the 50-57 ppbv range. These model results imply that SO_2 is not a significant problem in the United States, irrespective of aircraft. However, the model failed to capture many of the highest-magnitude SO_2 events. From Figure 2, it is clear that the actual number and magnitude of SO2 exceedances in 2005 were higher than predicted by this model. Nevertheless, the data indicate that aircraft are not an important contributor to SO_2 exceedance events.

EPA monitor data from 2006-2008 found that the top exceedances occur in rural counties, none of which experienced more than a 0.03 ppbv contribution to SO_2 concentration due to aircraft during the largest exceedance event included in the model (Table 5). Aircraft contribution to average SO_2 concentration was even lower, ranging from 0.001 - 0.003 ppbv (not included in table), two orders of magnitude smaller than average aircraft contribution to numerous other cells highlighted in Figure 3.

This implies that the worst violations tend to occur where aircraft are not major contributors. Counties like those in Table 5 likely account for the high-concentration outliers shown on the right side of Figure 2. Hence, it is probable that aircraft are not not significant contributors of SO_2 during large exceedance events.

3.3 Nitrogen Dioxide

The EPA recently announced the final selection of a 100 ppbv NO_2 standard,[7] a threshold considerably above the 65 ppbv limit which was the lower bound examined in this study and which was used to define NO_2 exceedance events. No events exceeding 100 ppbv were observed in any simulation. The EPA also plans to retain an annual average standard for NO_2 of 53 ppbv. However, no simulation produced an annual average value above 45 ppbv in any grid cell. This study focuses on the full range of proposed hourly NO_2 standards from Table 1.

In contrast to the results for SO_2 (in Table 2), there were thousands of modeled NO_2 exceedances, and aircraft contribution to NO_2 concentrations (on average and during exceedance events) was found to be 1 - 2 orders of magnitude greater than aircraft contribution to SO_2 concentrations (Table 6). Average aircraft contribution to exceedance events in 2005 is about double their average contribution to total NO_2 in that year. From 2005 to 2025, the fraction of total NO_2 concentration attributable to aircraft will grow faster than aircraft's contribution to exceedance events.

Statistic	**2005**	**2025**
Number of Exceedance Events (based on 65 ppbv std.)	4389 events	645 events
Exceedances due to Aircraft	148 events (3.37%)	46 events (7.13%)
Fraction of Annual Average [NO_2] due to Aircraft	0.20%	0.62%
Fraction of Exceedance Event [NO_2] due to Aircraft	0.39%	0.56%

Table 6: Summary statistics for NO_2

As shown in Table 7, the most NO_2 exceedances occurred in the Los Angeles area. New Orleans and New York City are the two next-most prominent regions. Table 8 illustrates that in 2025, aircraft contribution to exceedances in Los Angeles and New York City is even more important than in 2005. Aircraft will be responsible for 0.63% - 1.36% of Los Angeles exceedance concentrations and 2.53% - 7.48% of New York exceedance concentrations, several times greater than aircraft contribution to average exceedance events. New Orleans will continue to see little contribution from aircraft.

Figure 4 shows that at lower levels of the standard, aircraft make a noticeable difference in number of exceedance events. At higher levels of the standard, the effect of aircraft diminishes. In 2005, there were very few exceedance events above 90 ppbv, and by 2025, few will exceed 80 ppbv.

Figure 5 shows that exceedance events are heavily concentrated in a few cells around the country, generally in large urban areas. By 2025, only four metro areas (New Orleans, Los Angeles, Houston, and New York City) will

# Excd	row	col	Location	Avg Excd	Max Excd	Avg Aircraft Contrib	% Aircraft Contrib
1040	44	21	Los Angeles, CA	73.45 ppbv	98.33 ppbv	0.22 ppbv	0.29%
679	44	22	Los Angeles, CA	72.58 ppbv	97.97 ppbv	0.30 ppbv	0.42%
448	26	92	New Orleans, LA	71.66 ppbv	93.34 ppbv	0.05 ppbv	0.07%
443	44	20	Los Angeles, CA	71.01 ppbv	87.11 ppbv	0.47 ppbv	0.66%
296	44	23	Los Angeles, CA	70.40 ppbv	84.34 ppbv	0.32 ppbv	0.45%
196	43	21	Los Angeles, CA	70.72 ppbv	84.28 ppbv	0.19 ppbv	0.27%
165	66	128	New York City, NY	71.74 ppbv	98.20 ppbv	0.50 ppbv	0.69%
133	65	128	New York City, NY	73.40 ppbv	91.55 ppbv	0.89 ppbv	1.21%
106	45	21	Los Angeles, CA	70.34 ppbv	83.62 ppbv	0.20 ppbv	0.29%
91	43	22	Los Angeles, CA	69.07 ppbv	79.60 ppbv	0.18 ppbv	0.25%
75	25	79	Houston, TX	68.65 ppbv	78.51 ppbv	0.12 ppbv	0.17%
59	65	127	New York City, NY	69.91 ppbv	80.08 ppbv	0.45 ppbv	0.64%
44	26	93	New Orleans, LA	69.17 ppbv	78.70 ppbv	0.06 ppbv	0.09%
43	66	127	New York City, NY	70.27 ppbv	87.60 ppbv	0.27 ppbv	0.38%
36	63	96	Chicago, IL	68.64 ppbv	74.88 ppbv	0.24 ppbv	0.35%

Table 7: 2005 NO_2 Exceedances by Location (U.S. only, top 15 cells)

# Excd	row	col	Location	Avg Excd	Max Excd	Avg Aircraft Contrib	% Aircraft Contrib
289	26	92	New Orleans, LA	69.96 ppbv	89.54 ppbv	0.15 ppbv	0.21%
131	44	21	Los Angeles, CA	69.41 ppbv	77.94 ppbv	0.63 ppbv	0.91%
76	44	20	Los Angeles, CA	69.35 ppbv	77.86 ppbv	0.94 ppbv	1.36%
32	44	22	Los Angeles, CA	68.73 ppbv	73.51 ppbv	0.44 ppbv	0.63%
21	26	93	New Orleans, LA	69.10 ppbv	73.82 ppbv	0.15 ppbv	0.22%
9	25	80	Houston, TX	67.85 ppbv	70.32 ppbv	0.12 ppbv	0.17%
6	66	128	New York City, NY	69.61 ppbv	74.67 ppbv	1.97 ppbv	2.84%
3	65	127	New York City, NY	65.49 ppbv	65.76 ppbv	1.66 ppbv	2.53%
3	65	128	New York City, NY	66.75 ppbv	67.63 ppbv	4.99 ppbv	7.48%
2	28	90	New Orleans, LA	65.45 ppbv	65.53 ppbv	0.07 ppbv	0.11%
1	66	127	New York City, NY	67.05 ppbv	67.05 ppbv	2.92 ppbv	4.36%
Note: the remaining 72 exceedances were located near Monterrey, Mexico and Calgary, AB.							

Table 8: 2025 NO_2 Exceedances by Location (U.S. only, complete with 11 cells)

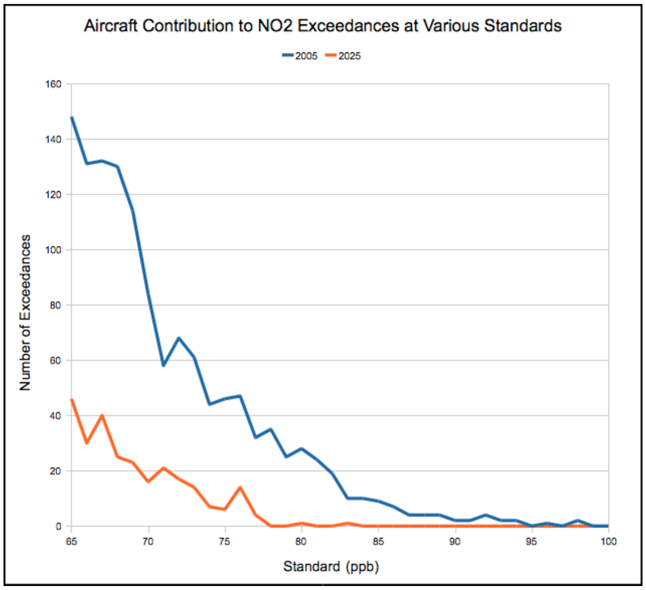

Figure 4: NO_2 Exceedances at Various Standards and Aircraft Contribution to those Exceedances

exceed a 65 ppbv NO_2 standard at least once per year. In Figure 6, we see that aircraft contribute over 0.02 ppbv to average NO_2 concentrations in many of the same areas where they contribute the most to SO_2 (Figure 3): large urban areas and major flight corridors.

Table 9 identifies Cook County (Chicago), Los Angeles County, Maricopa County (Phoenix), Union County (part of the New York City metro area), and Erie County (Buffalo, NY) as problematic areas. Relative to average exceedance event contributions (Table 6), aircraft are responsible for a

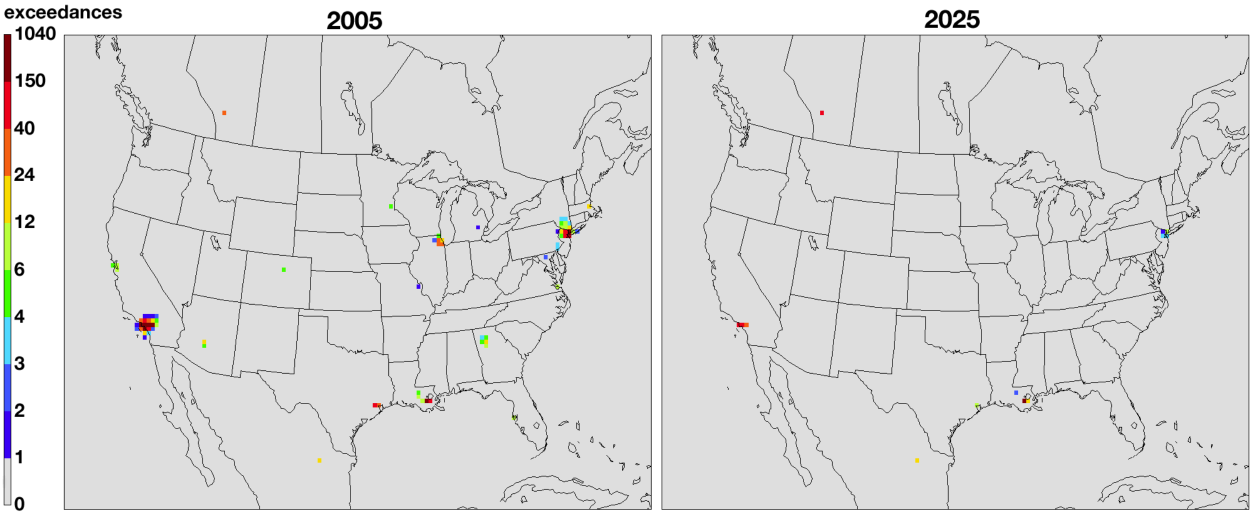

Figure 5: NO_2 Exceedance Events in 2005 and 2025 (# exceedances)

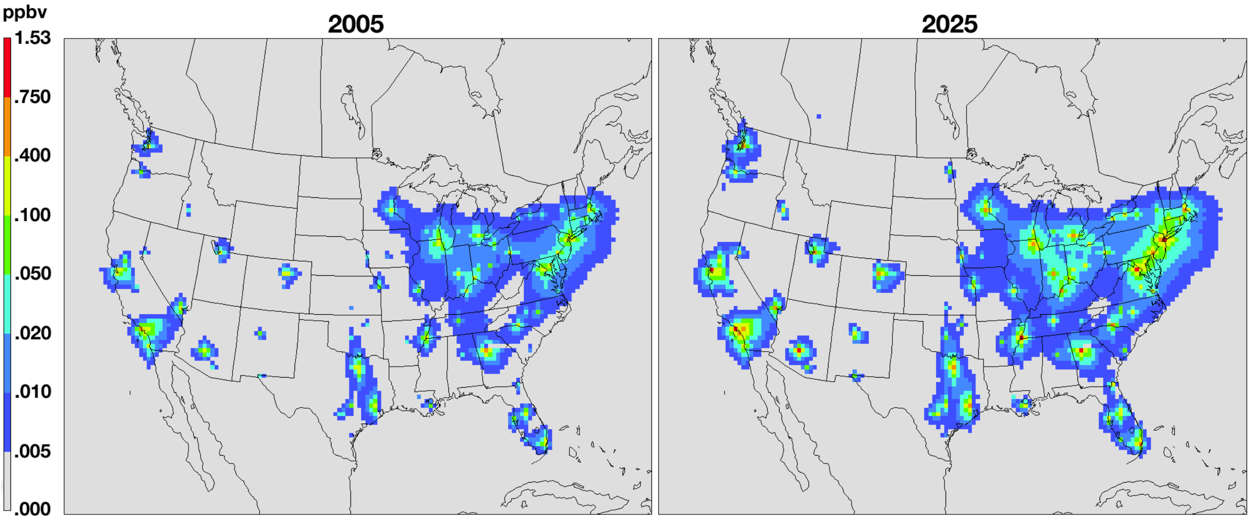

Figure 6: Aircraft Contribution to Annual Average NO_2 Concentration in 2005 and 2025 (ppbv)

greater portion of maximum exceedance concentration in Chicago and New York City, a similar share in Los Angeles and Phoenix, and a smaller portion in Buffalo. By 2025, aircraft are contributing much more than average to every one of these top exceedance areas except Buffalo. The change in Phoenix spans two orders of magnitude.

Model results (Tables 7-8 and Figure 5) indicate that NO_2 exceedance events tend to occur in major metropolitan areas, particularly Los Angeles, New Orleans, New York City, and Chicago. From Table 7, the contribution of aircraft to NO_2 during exceedance events in Los Angeles (0.25% - 0.66%) and New York City

County	Monitor Value	2005 Max Conc	2005 Aircraft Contrib	2025 Max Conc	2025 Aircraft Contrib
Cook, IL	106 ppbv	73.68 ppbv	1.08 ppbv (1.47%)	52.98 ppbv	1.76 ppbv (3.32%)
Los Angeles, CA	93 ppbv	87.11 ppbv	0.32 ppbv (0.37%)	77.86 ppbv	1.00 ppbv (1.28%)
Maricopa, AZ	93 ppbv	67.02 ppbv	0.25 ppbv (0.37%)	28.52 ppbv	3.20 ppbv (11.22%)
Union, NJ	91 ppbv	80.08 ppbv	0.61 ppbv (0.76%)	65.76 ppbv	1.44 ppbv (2.19%)
Erie, NY	88 ppbv	37.23 ppbv	0.04 ppbv (0.11%)	23.22 ppbv	0.05 ppbv (0.22%)

Table 9: Aircraft Contribution to Maximum NO_2 Concentrations in Counties with Highest Exceedances based on Measurements

(0.38% - 1.21%) was generally greater than their 0.39% contribution to average exceedance events (Table 6). New Orleans was an exception, with a below-average aircraft contribution of 0.07% - 0.09%. These data imply that in many– but not all– major metropolitan areas with NO_2 exceedances, aircraft contribution is substantially above average and may be a significant contributor to total NO_2 concentration.

Examination of the counties identified as top violators by 2006-2008 EPA monitor data leads to a similar conclusion. Except in Buffalo, aircraft contributions to maximum exceedance events were at least as great as their average contribution to exceedance events and were larger than their average contribution across all cells. Again, we find that in many major urban areas, large magnitude exceedances are correlated with unusually large aircraft contributions. This effect becomes much more pronounced in 2025.

3.4 Ozone

While the model found fewer than 100 exceedances for SO_2 (Table 2) and 645 to 4389 exceedances for NO_2 (Table 6), ozone exceedances numbered in the hundreds of thousands (Table 10). Aircraft's percentage contribution to these O_3 exceedances was roughly 10-20% of their contribution to NO_2 exceedances, but it was an order of magnitude greater than their contribution to SO_2 exceedances. Table 10 shows that the contribution of aircraft to O_3 exceedance events very nearly matches their contribution to domain-wide O_3 concentrations.

Statistic	2005	2025
Number of Exceedance Events (based on 60 ppbv std.)	348134 events	200620 events
Exceedances due to Aircraft	3139 events (0.90%)	5599 events (2.79%)
Fraction of Annual Average [O_3] due to Aircraft	0.04%	0.12%
Fraction of Exceedance Event [O_3] due to Aircraft	0.06%	0.15%

Table 10: Summary statistics for O_3

The areas around Denver, CO and California's San Joaquin valley had the greatest number of ozone exceedances (Table 11). Aircraft actually caused a decrease in ozone concentrations in some of these cells. In 2025, the effect of aircraft will be more pronounced than in 2005, resulting in either a greater contribution to O_3 or a greater reduction in O_3 in the cells with the most exceedances, as illustrated in Table 12.

At the levels of the O_3 standard under consideration by the EPA (60 ppbv - 70 ppbv), aircraft are predicted to be responsible for a greater absolute number of exceedances in 2025 than they were in 2005 (Figure 9). Above 70 ppbv, aircraft are responsible for more exceedances in 2005, because at that level of the standard, the decrease in number of exceedances begins to outweigh the increase in airplane contribution (from 0.90% of events in 2005 to 2.79% of events in 2025, Table 10).

Figure 10 shows that exceedances are spread across a large area of the country. They are most common in Colorado (in an area spanning nine counties which entered non-attainment in 2007),[8] southern California, and just

# Excd	row	col	Location	Avg Excd	Max Excd	Avg Aircraft Contrib	% Aircraft Contrib
124	54	56	Colorado Springs, CO	65.70 ppbv	91.35 ppbv	0.06 ppbv	0.09%
123	56	56	Denver, CO	66.63 ppbv	92.85 ppbv	0.09 ppbv	0.13%
123	58	56	Fort Collins, CO	66.50 ppbv	87.10 ppbv	0.09 ppbv	0.13%
121	57	55	Boulder, CO	66.97 ppbv	97.98 ppbv	-0.06 ppbv	-0.09%
121	55	56	Denver, CO	65.49 ppbv	93.77 ppbv	-0.03 ppbv	-0.04%
119	51	21	Visalia, CA	68.10 ppbv	84.16 ppbv	0.06 ppbv	0.09%
116	56	55	Denver, CO	66.12 ppbv	98.91 ppbv	0.11 ppbv	0.16%
116	59	56	Fort Collins, CO	65.75 ppbv	84.89 ppbv	0.02 ppbv	0.03%
115	27	94	New Orleans, LA	67.50 ppbv	88.70 ppbv	-0.02 ppbv	-0.04%
114	58	55	Boulder, CO	65.70 ppbv	93.49 ppbv	0.07 ppbv	0.10%
114	28	98	Mobile, AL	67.78 ppbv	91.50 ppbv	0.05 ppbv	0.07%
114	27	93	New Orleans, LA	68.12 ppbv	84.82 ppbv	0.04 ppbv	0.06%
113	56	54	Denver, CO	64.87 ppbv	90.30 ppbv	-0.08 ppbv	-0.12%
113	50	21	Bakersfield, CA	67.62 ppbv	84.27 ppbv	0.07 ppbv	0.10%
113	52	21	Visalia, CA	67.41 ppbv	79.83 ppbv	-0.01 ppbv	-0.01%

Table 11: 2005 O_3 Exceedances by Location (U.S. only, top 15 cells)

# Excd	row	col	Location	Avg Excd	Max Excd	Avg Aircraft Contrib	% Aircraft Contrib
108	56	56	Denver, CO	65.97 ppbv	85.21 ppbv	0.14 ppbv	0.22%
105	45	22	San Bernardino, CA	69.46 ppbv	99.42 ppbv	-0.01 ppbv	-0.01%
105	57	56	Denver, CO	66.54 ppbv	82.55 ppbv	0.25 ppbv	0.37%
103	57	55	Boulder, CO	66.00 ppbv	89.40 ppbv	0.04 ppbv	0.06%
97	45	19	Los Angeles, CA	68.54 ppbv	95.87 ppbv	-0.16 ppbv	-0.23%
96	44	24	Riverside, CA	67.76 ppbv	107.57 ppbv	-0.35 ppbv	-0.51%
95	45	23	San Bernardino, CA	68.21 ppbv	96.71 ppbv	0.32 ppbv	0.46%
94	58	56	Fort Collins, CO	65.49 ppbv	81.23 ppbv	0.21 ppbv	0.32%
93	45	24	San Bernardino, CA	68.26 ppbv	88.10 ppbv	0.33 ppbv	0.48%
92	45	25	Palm Springs, CA	66.96 ppbv	82.62 ppbv	0.18 ppbv	0.26%
91	54	56	Colorado Springs, CO	65.40 ppbv	83.38 ppbv	0.08 ppbv	0.12%
89	44	25	Palm Desert, CA	67.11 ppbv	91.55 ppbv	0.16 ppbv	0.23%
88	43	25	Palm Desert, CA	66.57 ppbv	98.41 ppbv	0.06 ppbv	0.09%
88	51	49	San Jaun Natn'l Forest, CO	65.00 ppbv	83.91 ppbv	0.03 ppbv	0.04%
87	56	55	Denver, CO	65.94 ppbv	89.08 ppbv	0.10 ppbv	0.15%

Table 12: 2025 O_3 Exceedances by Location (U.S. only, top 15 cells)

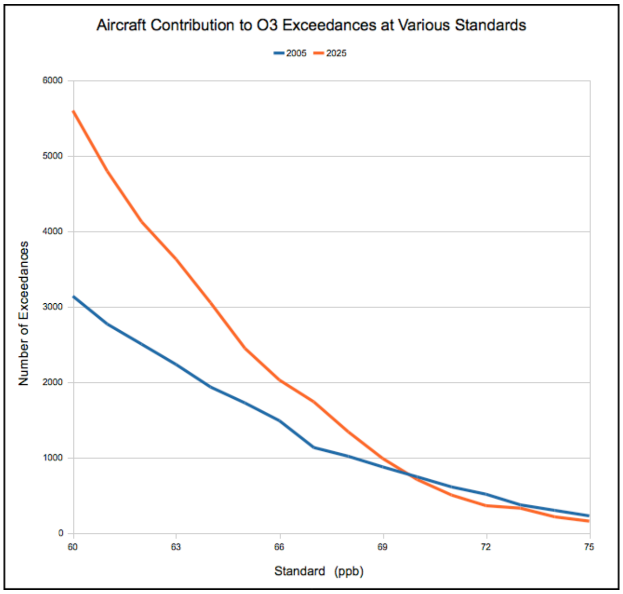

Figure 9: O_3 Exceedances at Various Standards and Aircraft Contribution to those Exceedances

off the east coast. Figure 11 is a map of the contribution of aircraft to the annual average of the maximum 8-hour average O_3 concentration (that is, an average of 365 O_3 concentrations, one per day, each of which is the highest 8-hour average O_3 concentration predicted for that day). This metric is similar to that used for NO_2 and SO_2 (Figures 3 and 6), but it more accurately reflects the method the EPA will use to determine ozone non-attainment areas. Figure 11 indicates that aircraft caused the largest increases in 8-hour maximum O_3

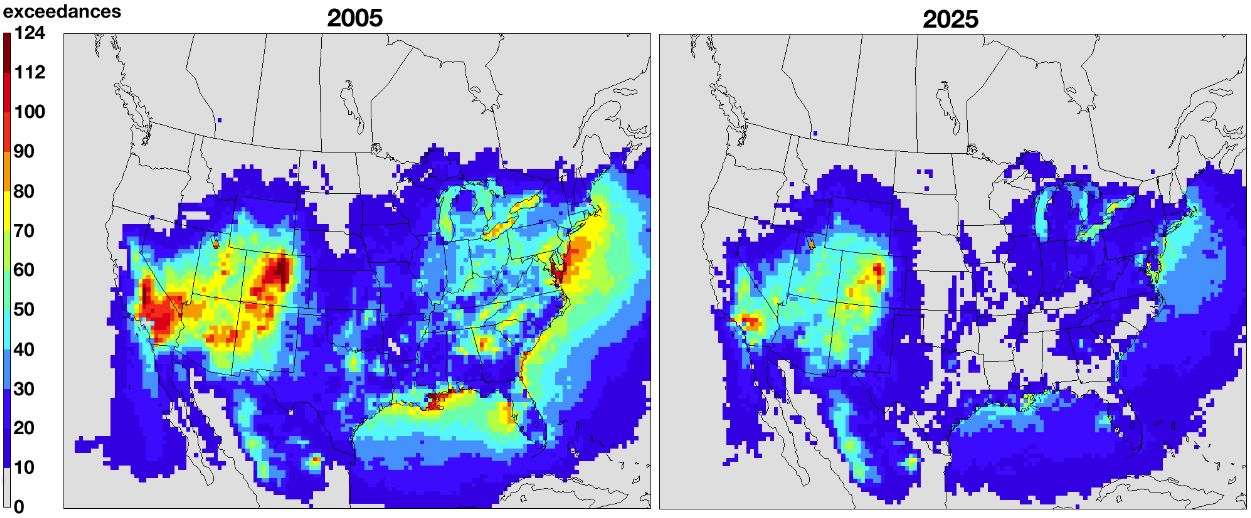

Figure 10: O_3 Exceedance Events in 2005 and 2025 (# exceedances)

concentration near Las Vegas, NV; Phoenix, AZ; Orlando, FL; and Miami, FL. Outside of urban areas, aircraft had comparatively little effect on O_3 concentrations in the northern half of the country. Many large urban areas (including New York City, Chicago, Boston, Minneapolis-St. Paul, Seattle, Los Angeles, and San Francisco) saw substantial reductions in ozone due to aircraft. Atlanta, Miami, Las Vegas, and Phoenix all experienced a reduction in O_3 due to aircraft (limited to the city center) in 2005 but a large increase in 2025.

Aircraft emissions are capable of reducing ozone concentrations in urban areas due to the nonlinear chemical processes which generate ozone. In cities where aircraft lowered O_3 concentrations, ozone production is likely in a VOC-limited (or NO_x-abundant) regime, so the additional NO_x emissions due to aircraft tend to inhibit further ozone formation by reacting with radicals needed to oxidize VOCs. (Aircraft themselves likely emit more than enough NO_x to offset their own VOC emissions.) In 2025, aircraft fail to lower O_3 concentrations in certain cities (those in the Southeast especially) because they are in regions with abundant biogenic VOC emissions and

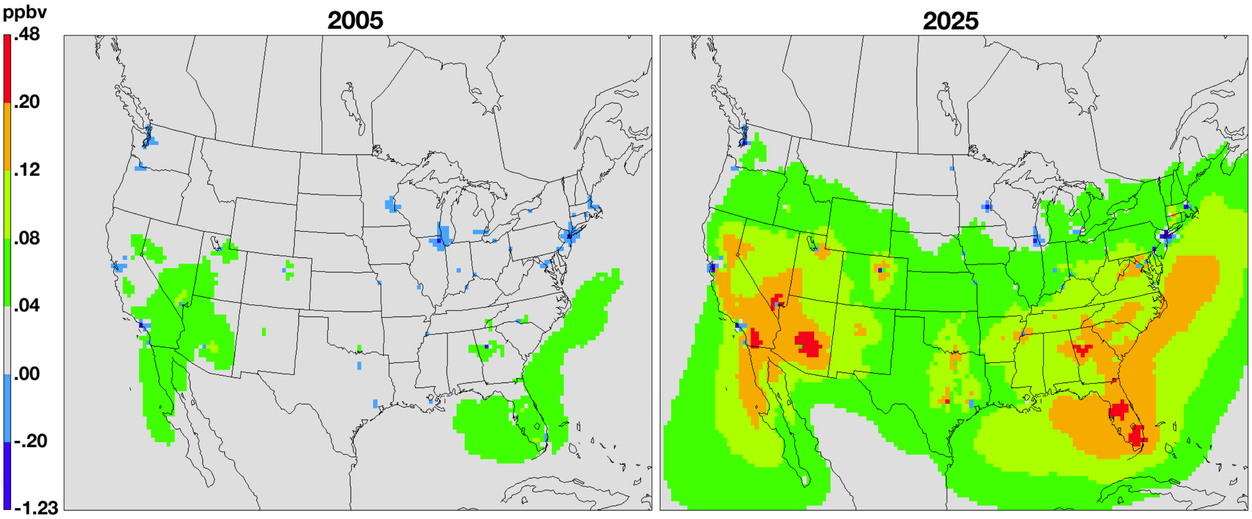

Figure 11: Aircraft Contribution to Annual Average of Maximum 8-Hour Average O_3 Concentration in 2005 and 2025 (ppbv)

therefore are not VOC-limited. Between 2005 and 2025, the city centers of Atlanta, Miami, Phoenix, and Las Vegas appear to transition from VOC-limited to NO_x-limited regimes due to anticipated reductions in non-aviation NO_x emissions. Note that Phoenix and Las Vegas are located in the desert, where high levels of biogenic emissions are unlikely, so there may be another reason why these cities are not VOC-limited in 2025.

Table 13 shows that the five worst O_3 violators according to 2006-2008 EPA monitor data were located in southern California. Aircraft contributed more to these exceedance events, either positively or negatively, than they did to average exceedance events in 2005 (0.06%) or 2025 (0.15%) (see Table 10).

County	Monitor Value	2005 Max Conc	2005 Aircraft Contrib	2025 Max Conc	2025 Aircraft Contrib
San Bernardino, CA	119 ppbv	88.01 ppbv	0.06 ppbv (0.07%)	76.37 ppbv	0.23 ppbv (0.30%)
Kern, CA	108 ppbv	81.60 ppbv	0.08 ppbv (0.10%)	73.29 ppbv	0.26 ppbv (0.35%)
Los Angeles, CA	108 ppbv	65.05 ppbv	-0.81 ppbv (-1.25%)	58.61 ppbv	-1.01 ppbv (-1.72%)
Riverside, CA	108 ppbv	91.76 ppbv	0.09 ppbv (0.10%)	84.13 ppbv	0.24 ppbv (0.29%)
Tulare, CA	105 ppbv	79.67 ppbv	0.18 ppbv (0.23%)	74.37 ppbv	0.33 ppbv (0.44%)

Table 13: Aircraft Contribution to Maximum O_3 Concentrations in Counties with Highest Exceedances based on Measurements

In Table 12, model results indicate that the greatest number of exceedances occur in Colorado, but the exceedances of greater maximum magnitude tend to be in southern California. This is supported by the 2006-2008 EPA monitor data in Table 13, which is based on magnitude of exceedances and highlights five counties in southern California as problem areas. Contribution of aircraft to maximum O_3 events is one to four times the average for the domain (from Table 10), except in Los Angeles itself, where aircraft sharply reduce ozone concentrations. NO_x is primarily emitted in the form of NO, which can react with O_3 in the immediate area of an emissions source to generate NO_2. However, this NO_2 will soon be converted back to ozone in a downwind area. This is a possible explanation for the data in Table 13 (in which all of the listed counties are near to Los Angeles).

Efforts to limit the NO_x emissions from aircraft to meet the new NO_2 standards may have the unintended consequence of worsening ozone problems in some major urban areas where airplane-derived NO_x suppresses O_3 formation. However, on the whole, aircraft are projected to contribute to ozone air pollution throughout much of the country by 2025 (see Figure 11), and dense urban areas which see O_3 reductions due to aircraft are likely offset by higher O_3 concentrations in surrounding areas. As such, efforts to reduce aircraft contribution to O_3 (particularly in the Southwest and Southeast) may be worthwhile.

4. Conclusions

Aircraft contribution to modeled SO_2 exceedances ranged from 0.00% to 0.05% (Tables 3-4), below aircraft's contribution to average SO_2 concentrations (0.05% in 2005, 0.14% in 2025, Table 2). Similarly, the contribution of aviation to maximum SO_2 concentrations in problem areas identified by the EPA (0.00 ppbv - 0.03

ppbv, Table 5) was less than its contribution to many other cells. These data indicate that aircraft are likely not an important contributor to SO_2 exceedance events, the worst of which tend to occur in rural areas where aircraft contribution is below average.

Aircraft contribute significantly to NO_2 exceedance events in some major urban areas around the country. New York City, Los Angeles, Chicago, and Phoenix in particular are places where there are large numbers of exceedances (Tables 7-8) or large magnitude exceedances (Table 9) and where aircraft make above-average contributions to NO_2 levels. By 2025, the fraction of maximum NO_2 concentrations attributable to aircraft in top exceedance areas is expected to increase between 2 and 30 times (see Buffalo and Phoenix in Table 9). However, there are some urban areas with many exceedances or large exceedances (such as New Orleans and Buffalo) where aircraft make a below-average contribution to NO_2 concentrations. Differences between urban areas may primarily be due to varying levels of air traffic, but airport placement, prevailing winds, and other factors could also be significant. These results imply that each urban area is unique and should be examined individually to determine if NO_x emission controls for aircraft are potentially beneficial in that area.

Aircraft increase ozone concentrations in the southern and western parts of the country, including some urban centers. However, they have little effect on ozone concentrations throughout the northern part of the country, and they tend to reduce ozone levels in many major urban areas (Figure 11). The O_3 decreases in these urban centers are likely due to the intricacies of NO_x- and VOC-related chemistry, as discussed in section 3.4. Counties which experienced violations of the largest magnitude were located in southern California and, without exception, experienced a maximum O_3 contribution from aircraft greater than aircraft's average contribution across the domain or to average exceedance events (Tables 10 and 13). Controlling emissions from aircraft may result in modest (<0.50%) air quality improvements in multi-county problem areas (Tables 11-13) but could increase maximum O_3 concentrations in urban centers by a larger margin (1.72% for Los Angeles, Table 13).

For NO_2 and O_3, the pollutants which are of relatively higher concern for aviation from the NAAQS perspective, aircraft will contribute more to exceedance events in 2025 than in 2005. Since aircraft emissions in this study included only landing and take-off cycles up to 10,000 ft. in altitude, the analysis presented here should be considered a lower bound on the potential effects of aviation emissions. Aircraft operators may wish to consider strategies to limit NO_2 emissions by 2025, particularly in urban areas.

5. Future Work

One potential direction for future research is to examine the role of aircraft in all counties which were found to be in non-attainment via EPA monitor data, not just the top five counties for each pollutant. This would provide a comprehensive assessment of the modeled effects of aviation emissions in areas that are likely to receive a non-attainment designation from the U.S. EPA. Another promising option would be to examine additional future years and several emissions projections for each future year based on alternate scenarios which assume different changes in technology or regulation. This could enable a researcher to make "high," "medium," and "low" estimates for the effects of aircraft in each future year. Finally, once emissions data for airplanes traveling at cruise altitudes become available, the analysis presented here could be repeated or expanded to determine the effect of high-altitude emissions on ground-level pollutant concentrations.

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