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# TRENDS IN WEATHER CORRECTED OZONE AND NITROGEN DIOXIDE UPDATED THROUGH 2019



## **TRENDS IN WEATHER CORRECTED OZONE AND NITROGEN DIOXIDE UPDATED THROUGH 2019**

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## 1. INTRODUCTION

Trends in weather corrected annual fourth highest maximum daily average 8-hour (MDA8) ozone concentrations, exceedances of the ozone standard in the high-concentration counties, and satellite-derived nitrogen dioxide (NO<sub>2</sub>) are presented in this report. In recent years, all of these parameters exhibit downward trends that are likely due to reductions in emissions. In addition, correlations between satellite NO<sub>2</sub> and weather corrected fourth highest MDA8 ozone values provide evidence that reductions in emissions have resulted in decreases in weather corrected ozone. It is also possible that recent, large reductions in NO<sub>x</sub> emissions at the Cherokee power generation facility north of downtown Denver have contributed to a recent downward trend in ozone at the NREL monitoring site.

This report is an update to the 2016 Trends in Weather Corrected Ozone and Nitrogen Dioxide report (CDPHE and RAQC, 2016) using data through the 2019 ozone season and contains language and text from the previous report.

## 2. TRENDS IN WEATHER CORRECTED OZONE

One of the elements of the weight of evidence supplemental analysis for the Denver Metro/North Front Range (DM/NFR) ozone State Implementation Plan (SIP) is an assessment of the effectiveness of historical emissions controls and their effects on trends in ozone concentrations at key monitoring sites. Both meteorology and emissions of ozone precursors have a direct impact on the magnitude and distribution of monitored peak ozone concentrations in Colorado's Front Range region. Historically, year-to-year variations in summer weather, however, have dominated the year-to-year changes in measured ozone. The impacts of emissions reductions or increases can be masked by the stronger influences of meteorology.

A variety of ozone trend-decomposition or filtering methods can be used to remove the effects of meteorology from an ozone time series. This filtering or decomposition can make it possible to see the effects of changes in emissions on ozone concentrations in relative isolation from many of the meteorological factors that also affect ozone concentrations. For the Early Action Compact of 2004 (Colorado Department of Public Health and Environment, 2004), the Zurbenko-Rao method (Porter et al., 1996; Eskridge et al., 1997; Rao et al., 1997) was used to cleanly separate ozone time series into distinct short and long-term components. Since this time, CDPHE has used a method developed specifically for use in Colorado and other western states.

Reddy and Pfister (2016) completed a thorough investigation of the impacts of weather and meteorology on the interannual variation of peak summer ozone in Colorado, Utah, and other Western states. They concluded that the meteorological variable that best predicts the effects of weather on July ozone is the mean strength of the upper-level high pressure systems over the monitors of interest. This upper-level high pressure strength is expressed as the 500 millibar (mb) height (or the distance above ground at which the air pressure is roughly half of mean sea level pressure). They found, for example, that upper-level high pressure strength accounts for 86% of the year-to-year variance in mean July MDA8 ozone concentrations at the Rocky Flats North (RFNO) monitor from 1995 through 2013.

They outlined a method for correcting mean July historical ozone time series for the effects of weather based on 500 mb heights. This method relies on the use of National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data for 500 mb heights as described by Kalnay et al. (1996). NCEP reanalysis data was obtained from the NOAA/OAR/ESRL PSL, Boulder, Colorado, USA, from their Web site at <https://psl.noaa.gov/>. The mean 500 mb heights are calculated for the 2.5 by 2.5 degree reanalysis grid cell that contains the DM/NFR ozone nonattainment area (NAA) and much of the Front Range. A map of this grid cell can be found in Figure S1 of the supporting information in the paper by Reddy and Pfister (2016), and this grid cell represents much of the area that could be considered the local airshed for summer ozone. This grid cell for the Front Range extends from near Colorado Springs, north to near Cheyenne, Wyoming, and from near Fort Morgan west to near Glenwood Springs (essentially the northern Front Range and north central mountains of Colorado). The resulting corrected historical values can be used to assess the effects of precursor emissions controls on ozone. This method is based on the linear regression of site-specific

ozone against 500 mb heights and the addition of the resulting positive or negative residuals to the mean ozone values for the period of interest for the given site.

While the historical fourth highest MDA8 ozone values are less strongly correlated with upper-level high pressure strength than mean July daily maximum 8-hour ozone, annual fourth max ozone concentrations have been regressed against mean June through August 500 mb heights for Denver for 1995 through 2019. For Rocky Flats North, NREL, and Chatfield, one to two years were determined to be outliers and removed from the analysis to obtain the final regression statistics in the 1995 through 2015 time series as reported in the Trends in Weather Corrected Ozone and Nitrogen Dioxide report (CDPHE and RAQC, 2016). Outliers were identified using the studentized residual metric in up to two passes of the regression analysis. In keeping with the method outlined by Reddy and Pfister (2016), fourth high MDA8 ozone for years with a studentized residual of 3.0 or higher were removed from the analysis. In the current analysis for 1995 through 2019, these outliers were left out of the updated analyses.

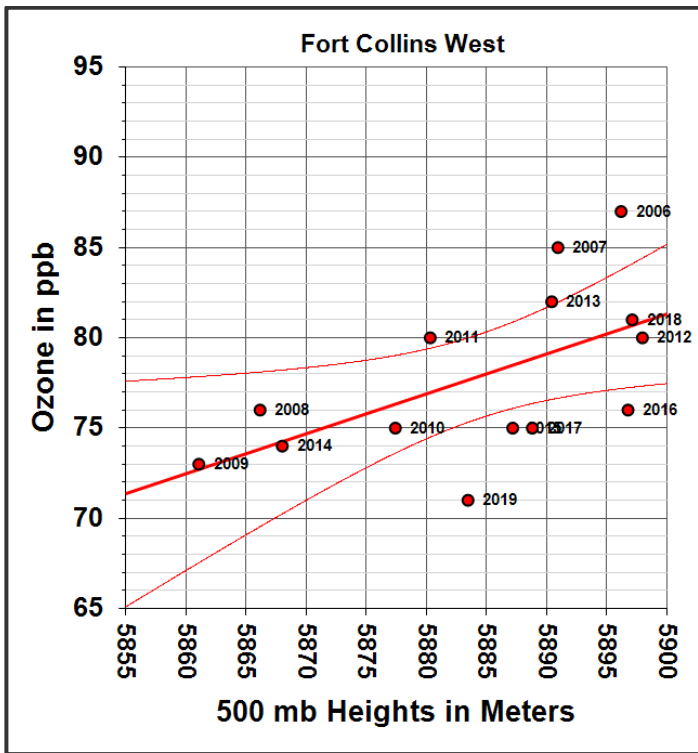
For the four highest-concentration sites along the Front Range (Rocky Flats North, NREL, Fort Collins West, and Chatfield), these regressions show that mean summer upper-level high pressure strength accounts for an average of 39% of the variance in year-to-year peak MDA8 ozone at these sites compared to the 61% identified in the 1995-2015 analyses. This means that weather accounts for much of the year-to-year changes in ozone, but significantly less than reported in the 2016 report. This reduction suggests that, since 2015, year-to-year changes in emissions are having a greater influence on ozone than in the past. From 2000-2019, the relationship between ozone and 500 mb heights at the CAMP site is still high with an r-squared of 0.78 (78% of the variance). Despite the reductions in r-squared values at the high sites in the current analyses, the correction method should reveal any significant changes due to changes in emissions alone. The details of this regression analysis are presented in Table 2-1.

**Table 2-1. Correlation coefficients, R-squared, outlier years removed, and number of years of data used for regressions of the annual fourth maximum ozone against mean July through August 500 millibar heights at the four high concentration sites along the Front Range for 1995 through 2015 and in downtown Denver at the CAMP site.**

Site	Pearson Correlation Coefficient	R-squared	Outlier Years Removed	Remaining Years of Data Used
Fort Collins West	0.58	0.33		14*
Rocky Flats North	0.52	0.27	1998	24
NREL	0.67	0.45	1998,2003	23
Chatfield	0.71	0.50	2003,2005	23
CAMP	0.88	0.78		13*

\*Ft. Collins West data record only covers 2006-2019; CAMP operated discontinuously from 2000-2019

Figure 2-1 through Figure 2-4 show the relationship between annual fourth highest MDA8 ozone concentrations and June through August monthly mean 500-millibar heights at Fort Collins West, Rocky Flats North, NREL, and Chatfield Reservoir, respectively. These plots include the linear regression (straight line) and the confidence limits for the regression (curved line).



**Figure 2-1. Linear regression with confidence limits of Fort Collins West annual fourth highest MDA8 ozone versus mean June through August 500 mb heights.**

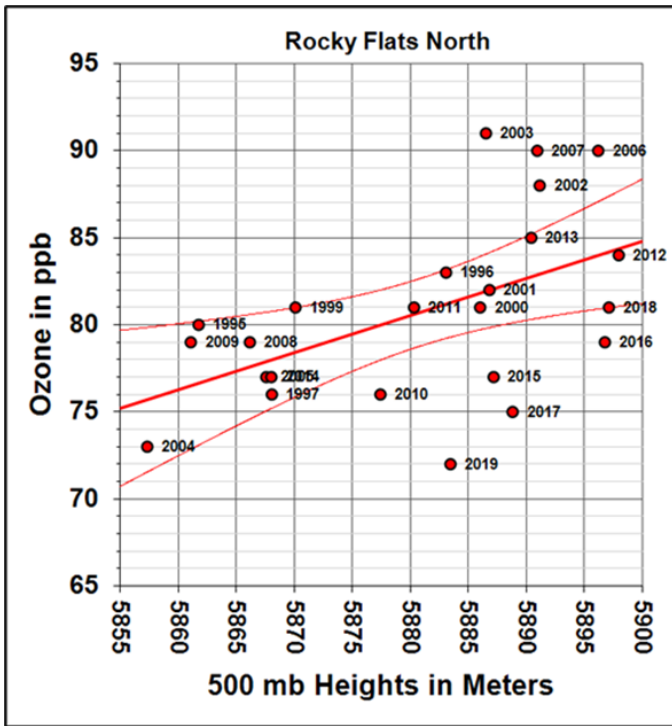


Figure 2-2. Linear regression with confidence limits of Rocky Flats North annual fourth highest MDA8 ozone versus mean June through August 500 mb heights.

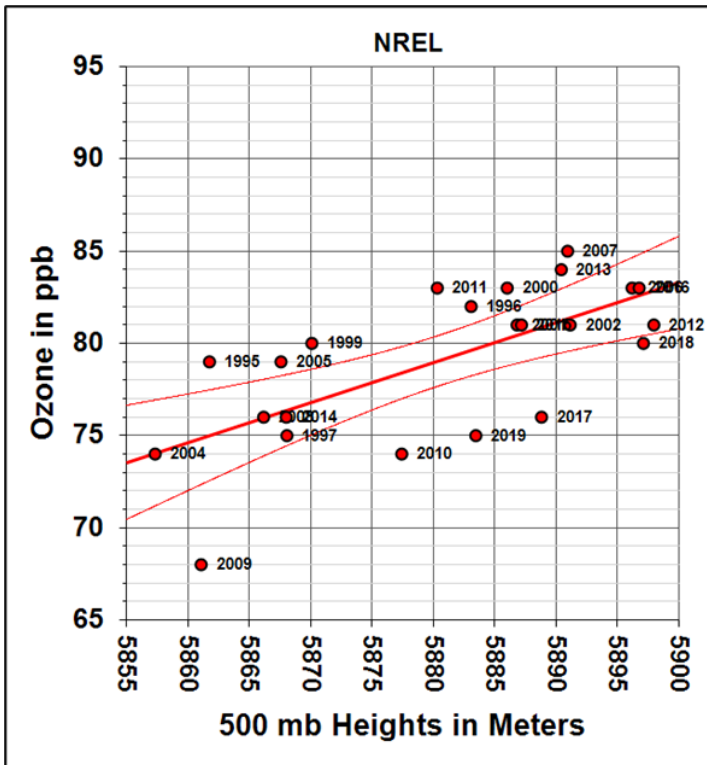
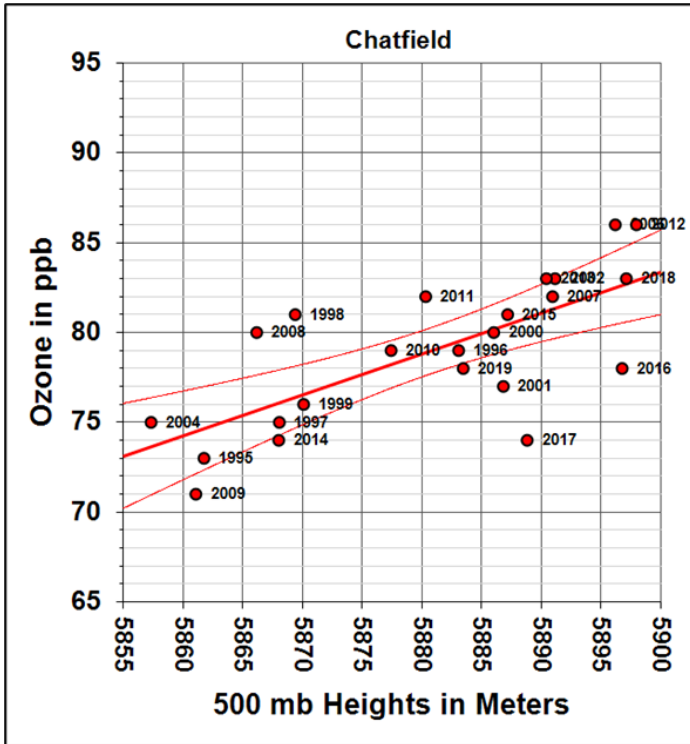
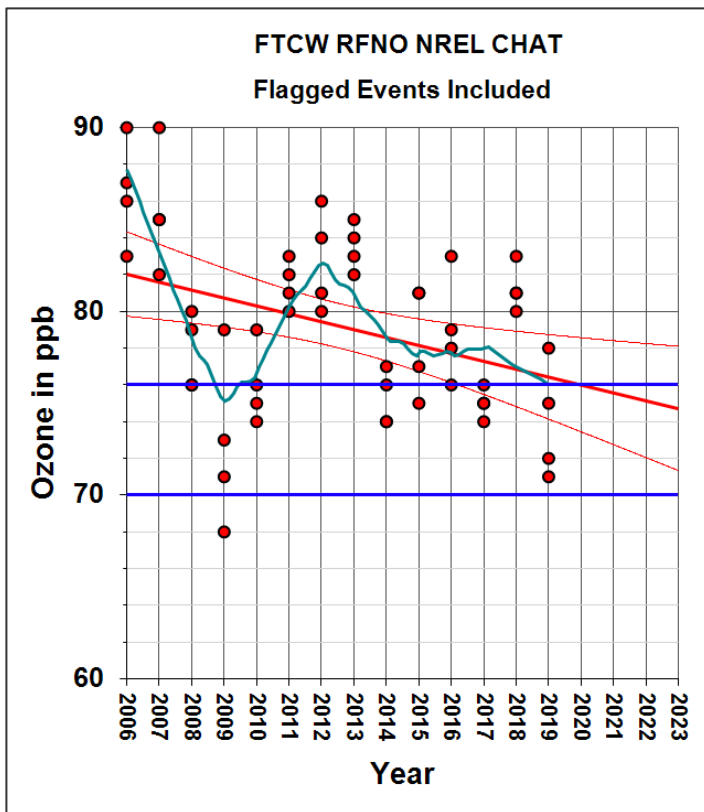


Figure 2-3. Linear regression with confidence limits of NREL annual fourth highest MDA8 ozone versus mean June through August 500 mb heights.



**Figure 2-4. Linear regression with confidence limits of Chatfield annual fourth highest MDA8 ozone versus mean June through August 500 mb heights.**

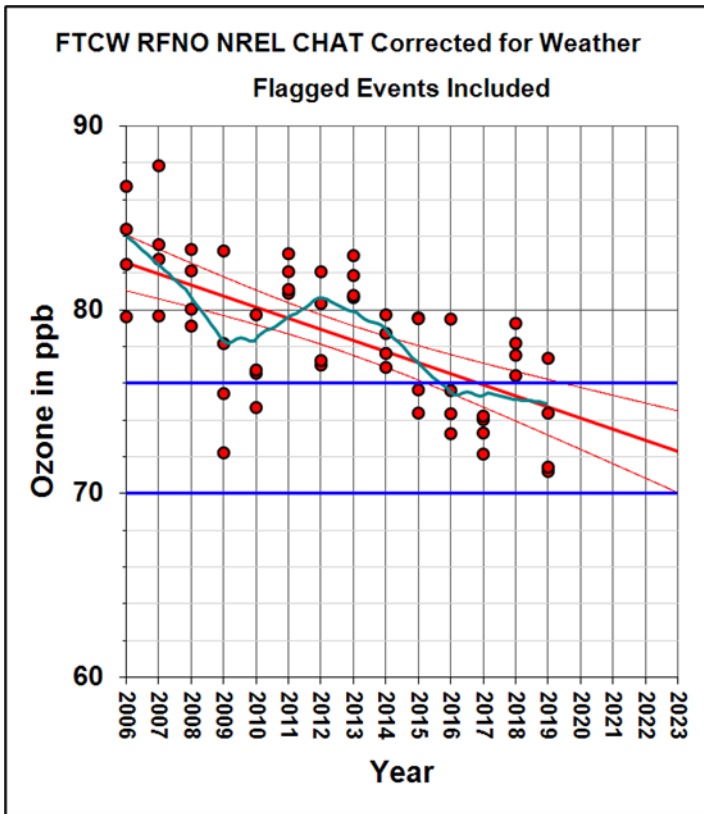
Figure 2-5 shows the composite trends for fourth highest MDA8 ozone at Fort Collins West, Rocky Flats North, NREL, and Chatfield. The straight red line and curved red lines in Figure 2-5 show a linear regression with confidence limits of ozone versus year, and these show a downward trend in ozone. The blue-green line is a locally estimated scatterplot smoothing (LOESS) smoothing curve (Cleveland, 1979) with a smoothing parameter of 0.30. The LOESS curve responds more readily to shorter-term changes in ozone than the regression line, and it reflects an apparent multi-year cycle in peak ozone at these sites that is probably related to multi-year cycles in weather. The regression line has a statistically significant downward slope (with an r-squared of 0.13), and it crosses 76 ppb in 2020 and is slightly below 75 ppb in 2023. This trend is based on historical data and does not account for any accelerated emissions reductions that might occur after 2019, the effects of weather, and exceptional events.



**Figure 2-5. Composite trends in fourth highest MDA8 ozone at Fort Collins West, Rocky Flats North, NREL, and Chatfield. Red lines are the linear regression with confidence limits, the blue-green line is the LOESS curve, and the straight blue lines are the measured exceedance levels for the standards (76 ppb and 70 ppb).**

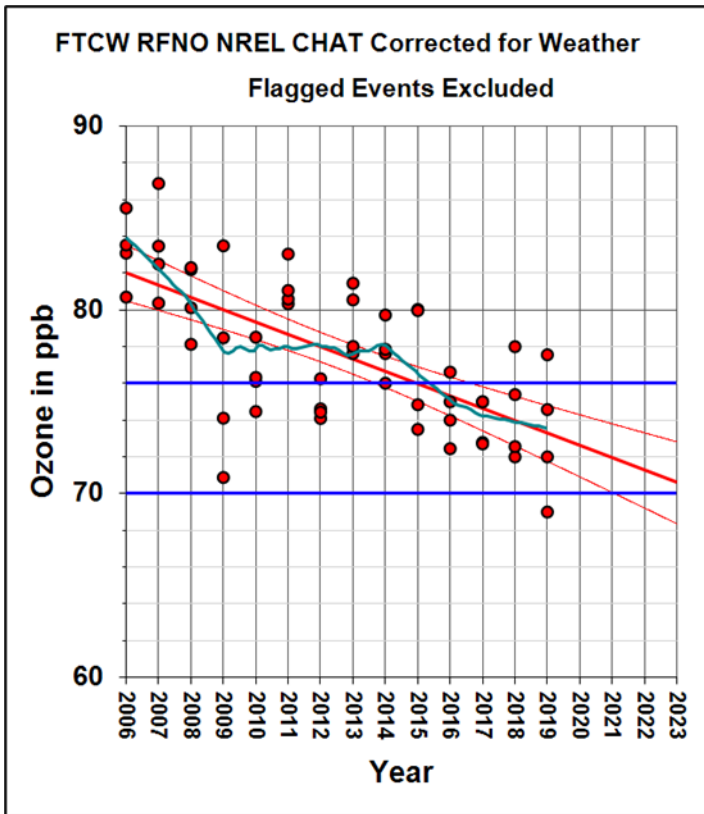
The resulting composite trends for weather-corrected fourth maximum ozone at Fort Collins West, Rocky Flats North, NREL, and Chatfield are presented in Figure 2-6. These trends include values flagged as possible exceptional events due to wildfire smoke or stratospheric intrusions of ozone. These ozone concentrations and trends also reflect the expected ozone each year under average weather conditions.

The straight red line and curved red lines in Figure 2-6 show a linear regression with confidence limits of ozone versus year, and these show a statistically significant downward trend in ozone. The LOESS curve suggests a steady decline in peak ozone beginning in 2012 which could be the result of decreases in either VOCs, NO<sub>x</sub>, or both. The regression line has a statistically significant downward slope (with an r-squared of 0.41), and it crosses 74 ppb in 2020 and is slightly above 72 ppb in 2023. This trend is based on historical data and does not account for any accelerated emissions reductions that might occur after 2019 or exceptional events.



**Figure 2-6. Composite trends in weather-corrected fourth highest MDA8 ozone at Fort Collins West, Rocky Flats North, NREL, and Chatfield. Red lines are the linear regression with confidence limits, the blue-green line is the LOESS curve, and the straight blue lines are the measured exceedance levels for the standard (76 ppb and 70 ppb).**

The composite trends of fourth highest MDA8 ozone values with the exclusion of events during 2010 through 2019 that occurred on days flagged as likely ozone exceptional events (with excess ozone from wildfire smoke or stratospheric intrusions) are presented in Figure 2-7. Here again the plot includes red lines for the linear regression with confidence limits showing a statistically significant downward trend in ozone and the blue green line for a LOESS curve with a smoothing parameter of 0.30. The regression line has a statistically significant downward slope (with an r-squared of 0.46), and it crosses between 72 and 73 ppb in 2020 and between 70 and 71 ppb in 2023. This trend is based on historical data and does not account for any accelerated emissions reductions that might occur after 2019.



**Figure 2-7. Composite trends in weather-corrected fourth highest MDA8 ozone at Fort Collins West, Rocky Flats North, NREL, and Chatfield with values flagged as exceptional events (2010 through 2014) removed. Red lines are the linear regression with confidence limits, the blue-green line is the LOESS curve, and the straight blue line is the measured exceedance level for the standard (76 ppb).**

Regressions between Rocky Flats North and Fort Collins West ozone and 500 mb heights through 2019 were not statistically significant after the flagged events had been removed and new fourth highest MDA8 ozone values had been calculated. Slopes of the regressions were not statistically different from zero, and the r-squared values for Rocky Flats North and Fort Collins West were 0.13 and 0.12, respectively. Regressions between fourth highest ozone values with flagged events removed for data through 2015 were calculated. For these regressions, the r-squared values were 0.40 and 0.55 for Rocky Flats North and Fort Collins West, respectively, and the regressions were statistically significant. For 2016 through 2019, the uncorrected fourth highest ozone values with flagged events removed were substituted into the time series to complete the trend lines for weather corrected time series (with flagged events removed).

These procedures are reasonable for these two sites since it is likely that the 2016-2019 data are more strongly affected by changes in emissions than weather. The substitution of raw fourth max ozone with flagged events excluded for these years continues the downward trends for the corrected data through 2015.

Trend lines for the individual high-ozone sites show that the downward trends are robust at Fort Collins West and Rocky Flats North, a little weaker at Chatfield, and statistically indeterminate at NREL.

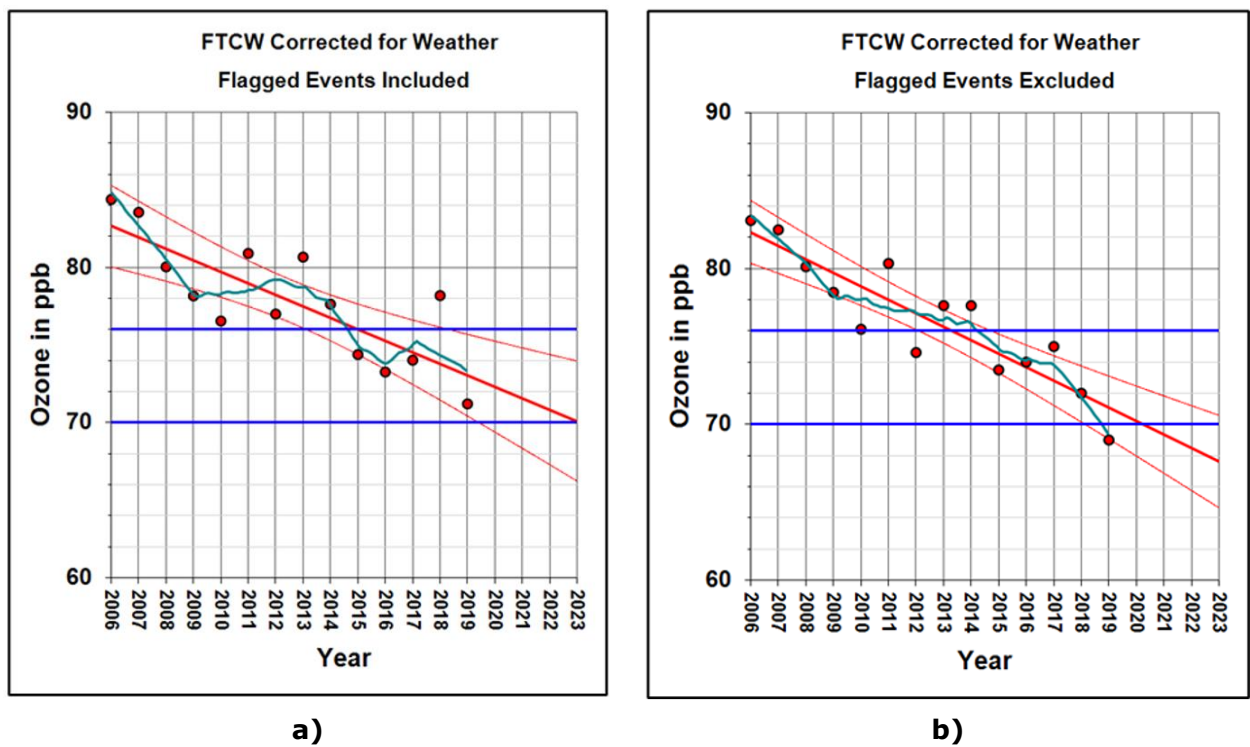
a)

b)

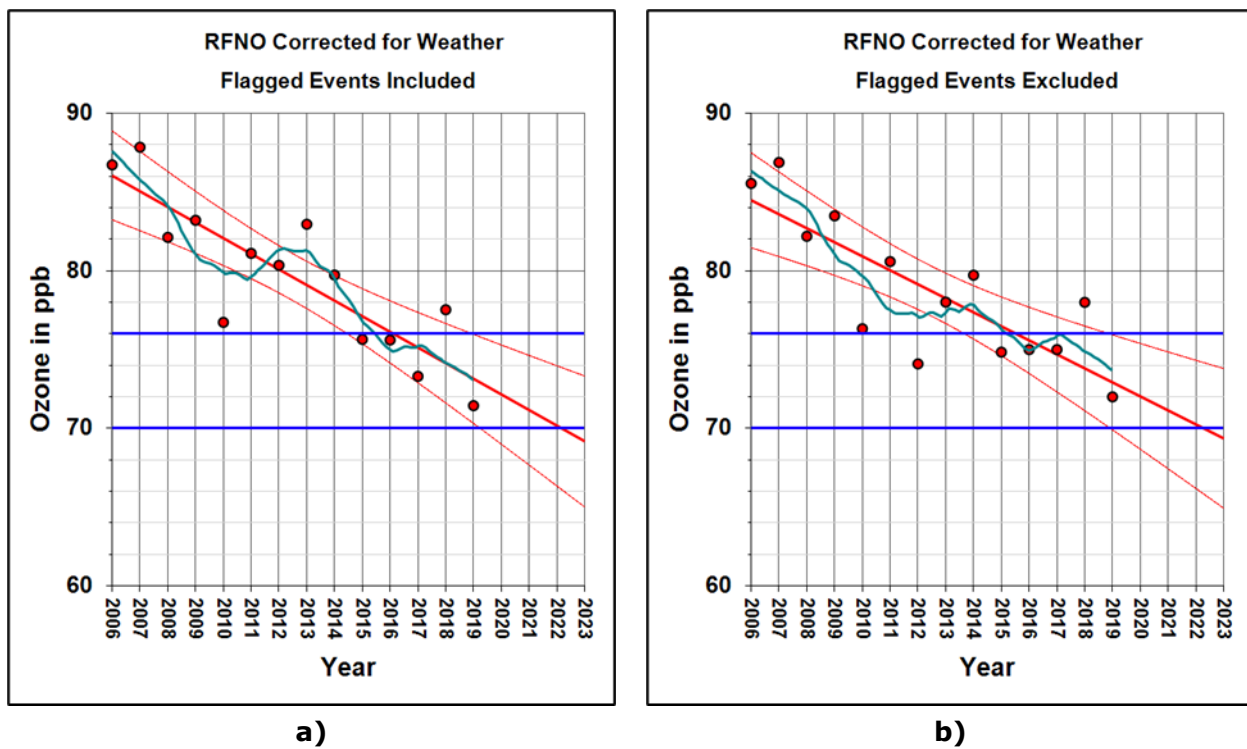
Figure 2-8 through Figure 2-11 show the weather-corrected trends with and without exceptional events for Fort Collins West, Rocky Flats North, NREL, and Chatfield, respectively. Table 2-2 shows the projected 2020 fourth max ozone at each of these sites for each of the two trend analyses. Rocky Flats North and Fort Collins West are at or below 70 ppb under each scenario by 2023. NREL is only below 70 ppb by 2023 when trends in weather corrected ozone with flagged events removed are calculated for 2011-2019 as shown in Figure 10c. Chatfield remains above 70 ppb by 2023 under each of the two trend scenarios.

**Table 2-2. Forecast 2020 fourth maximum ozone at the four high-concentration sites based on weather corrected ozone regressions and weather corrected ozone regressions with flagged events removed.**

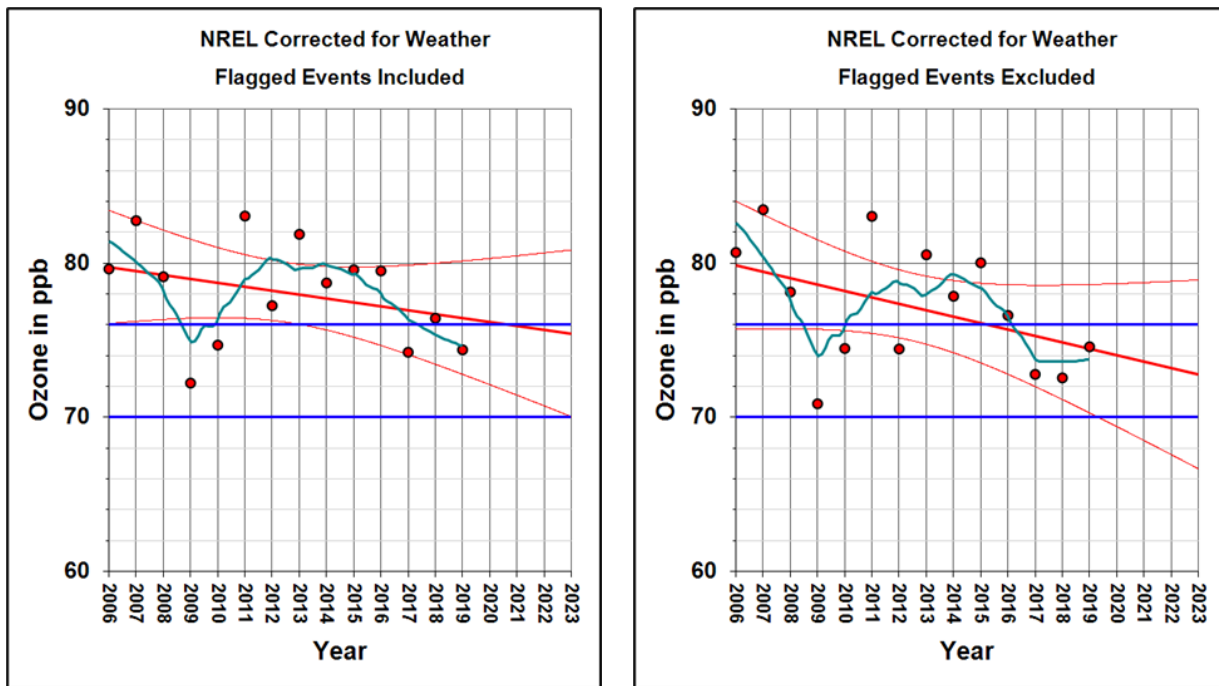
Site	Forecast 2020 Ozone in ppb Weather Corrected with Exceptional Events Included	Forecast 2020 Ozone in ppb Weather Corrected with Exceptional Events Excluded
Fort Collins West	72.4	70.1
Rocky Flats North	72.2	72.0
NREL	76.1	74.0
Chatfield	75.8	74.1



**Figure 2-8. (a) Trends in weather-corrected fourth highest MDA8 ozone at Fort Collins West. Red lines are the linear regression with confidence limits, the blue-green line is the LOESS curve, and the straight blue lines are the measured exceedance levels for the standards (76 ppb and 70 ppb) and (b) with values flagged as exceptional events (2010 through 2019) removed.**

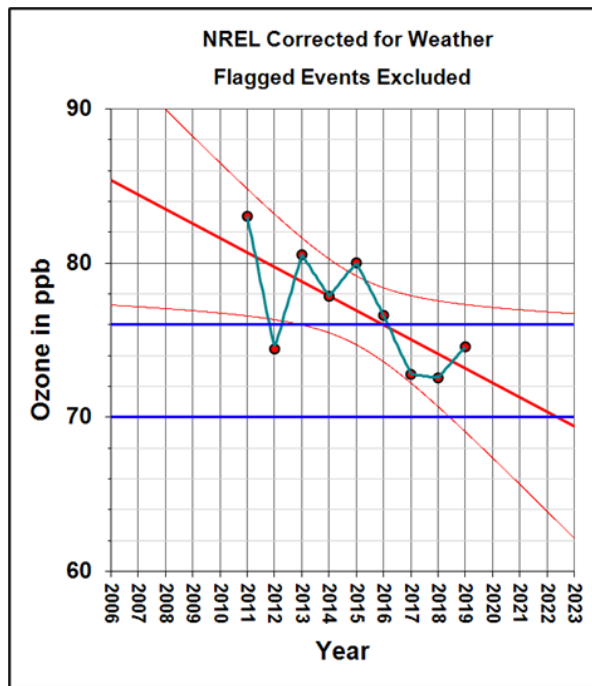


**Figure 2-9. a) Trends in weather-corrected fourth highest MDA8 ozone at Rocky Flats North. Red lines are the linear regression with confidence limits, the blue-green line is the LOESS curve, and the straight blue lines are the measured exceedance levels for the standards (76 ppb and 70 ppb) and (b) with values flagged as exceptional events (2010 through 2019) removed.**



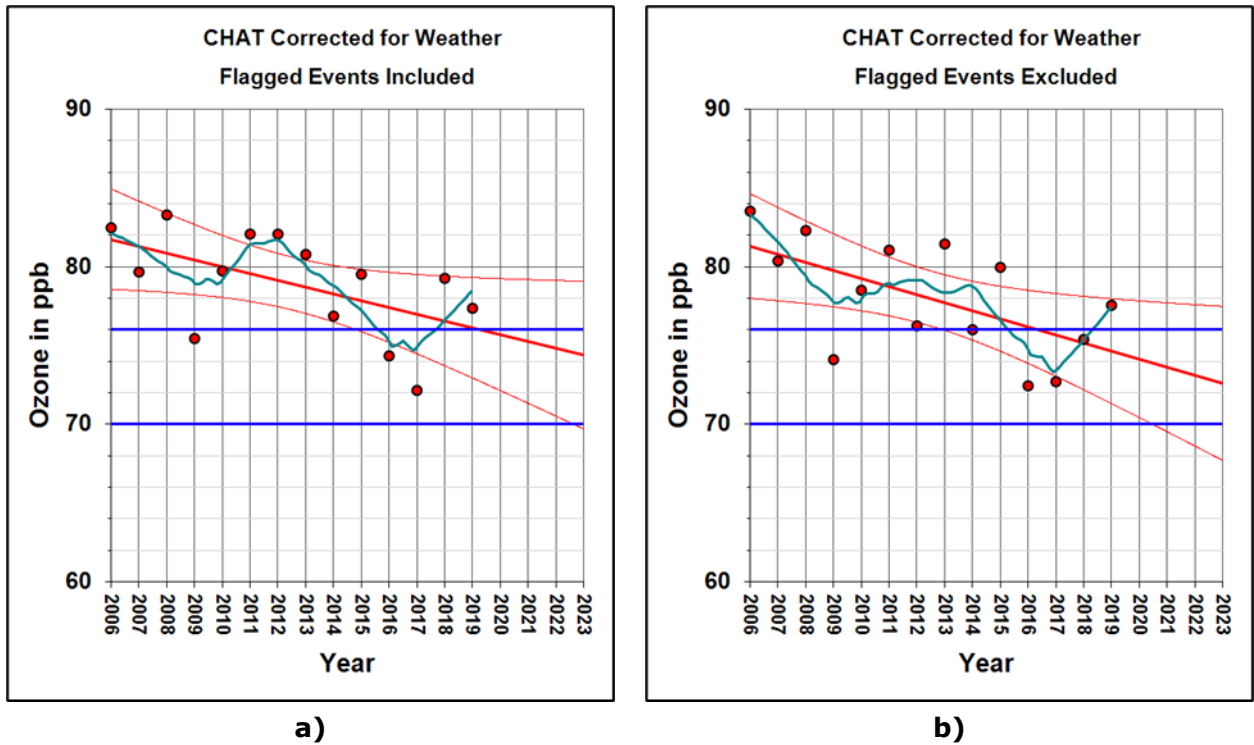
a)

b)



c)

**Figure 2-10.** (a) Trends in weather-corrected fourth highest MDA8 ozone at NREL. Red lines are the linear regression with confidence limits, the blue-green line is the LOESS curve, and the straight blue lines are the measured exceedance levels for the standards (76 ppb and 70 ppb); (b) with values flagged as exceptional events (2010 through 2019) removed; and (c) for 2010-2019 data with flagged events removed.



**Figure 2-11. (a) Trends in weather-corrected fourth highest MDA8 ozone at Chatfield. Red lines are the linear regression with confidence limits, the blue-green line is the LOESS curve, and the straight blue lines are the measured exceedance levels for the standards (76 and 70 ppb) and (b) with values flagged as exceptional events (2010 through 2019) removed.**

As NO<sub>x</sub> emissions from mobile sources are reduced in central Denver and there is less NO available for titrating (removing) ozone, it is expected that sites such as CAMP will see increases in ozone. Figure 2-12 shows (a) the raw trend in annual fourth maximum ozone at CAMP and (b) the weather corrected trend based on mean June through August 500 mb heights. The increasing trend is apparent, and the weather corrected trend shows that ozone is projected to remain below the 70 ppb standard through 2023. The trend for uncorrected ozone has greater uncertainty.

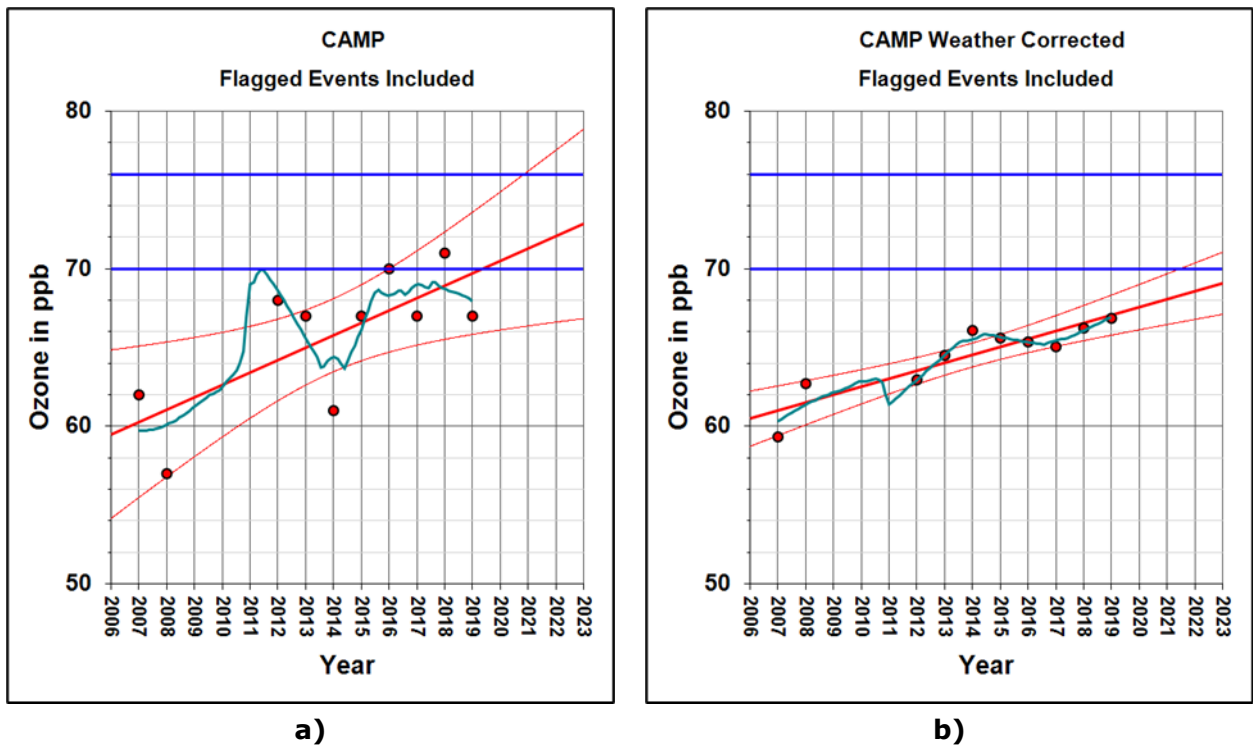


Figure 2-12. (a) Trends in raw fourth highest MDA8 ozone at CAMP in central Denver. Red lines are the linear regression with confidence limits, the blue-green line is the LOESS curve, and the straight blue lines are the measured exceedance levels for the standards (76 ppb and 70 ppb) and (b) with corrections for weather.

### 3. TRENDS IN WEATHER CORRECTED EXCEEDANCE DAY COUNTS

Trends in the number of exceedance days per year ("counts") of the ozone standard have also been corrected for the effects of weather. The method used involves regressing the natural logs of counts against the mean June through August 500 mb heights as described in the previous trends analysis report (CDPHE and RAQC, 2016). The highest-concentration ozone sites along the Front Range are found in Larimer, Jefferson, and Douglas Counties. Annual ozone standard county-exceedance-day counts for all monitors in these counties for 2006 through 2019 were obtained from the EPA ([https://www3.epa.gov/airdata/ad\\_viz\\_ozcompare.html](https://www3.epa.gov/airdata/ad_viz_ozcompare.html)). Here the counts are defined as the number of days per year that an exceedance of the 70 ppb 2015 ozone NAAQS occurred in each of the three counties listed previously. For example, a single day in which a monitor in each county recorded an exceedance would count as 3 counts. The natural log values of the aggregate exceedance counts for these counties have been found to be strongly correlated with mean June through August 500 mb heights (with a Pearson correlation of 0.6 and an r-squared value of 0.36).

The relationship between exceedance counts and 500 mb heights has been used to develop trends in weather-corrected counts following procedures similar to those used to correct annual fourth highest MDA8 ozone. Figure 3-1 shows the raw trend and resulting weather-corrected trend in counts. The correlation between weather corrected counts and year is 0.68 and the regression line has an r-squared value of 0.46. The weather-corrected trend indicates exceedance days in this three-county area would approach approximately 24 by 2023.

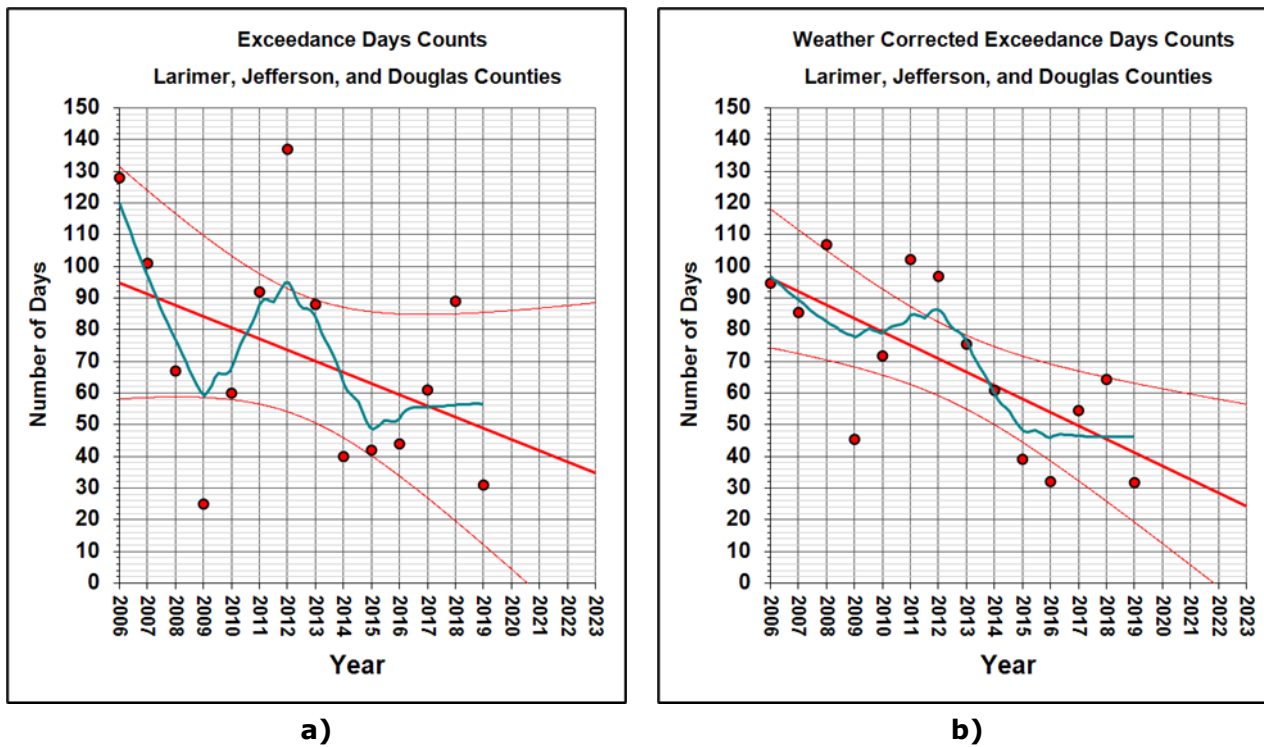


Figure 3-1. Trends in total Larimer, Jefferson, and Douglas County raw ozone exceedance day counts (a) and (b) weather-corrected counts. Red lines are the linear regression with confidence limits, the blue-green line is the LOESS smoothing curve.

## 4. TRENDS IN SATELLITE NO<sub>2</sub>

Satellite measurements of tropospheric NO<sub>2</sub> show steady declines during the period of interest. The satellite tropospheric NO<sub>2</sub> analyses are based on data from the Ozone Monitoring Instrument (OMI) which is aboard NASA's Aura satellite (see <https://aura.gsfc.nasa.gov/>). We obtained the data using NASA's Giovanni website (<https://aura.gsfc.nasa.gov/omi.html>), which enables a user to select a satellite data product and perform spatial and temporal averaging and data extraction. The OMI tropospheric NO<sub>2</sub> column product estimates the number of molecules of NO<sub>2</sub> in an atmospheric column from the earth's surface to the top of the troposphere (~10 km). The measurements are based on molecular absorption of backscattered sunlight in the visible and ultraviolet wavelengths and are processed to remove the contribution from the upper atmosphere (i.e. above the troposphere).

Good quality data with near clear sky conditions (i.e. cloud radiance fraction < 30 %) are binned and averaged to produce a global daily product with 0.25 by 0.25 degree (~25-km) grid resolution, which is available on the Giovanni website. The satellite product is called "OMNO2d: OMI/Aura NO<sub>2</sub> Cloud-Screened Tropospheric Column L3 Global Gridded 0.25 degree by 0.25 degree V3" (Krotkov et al, 2019). L3 indicates "Level 3" data which means that the data processing includes spatial allocation to a uniform grid. This is in contrast to a lower level of processing for which data is provided in a raw spatial format that consists of swaths of daily data that correspond to the satellite orbit for that day. The geometry of the swaths and pixels vary by day and there are different pixel sizes throughout the swath. V3 is "Version 3" which indicates the algorithms version used for converting the backscattered radiation to estimates of number of molecules in the atmospheric column. NASA updates the processing algorithms periodically which results in revised column estimates. When this occurs, column estimates for all prior years (~2005 to present) are revised simultaneously. Note that the algorithms were updated in December 2019, so NO<sub>2</sub> column results in this report may differ from previous results based on data prior to December 2019.

Mean June through August OMI tropospheric NO<sub>2</sub> column totals were calculated for 2006 through 2019 for the 2.5 by 2.5 degree reanalysis grid cell described earlier in this report that corresponds to much of the Front Range including the DM/NFR ozone NAA. Annual fourth highest MDA8 ozone concentrations for the four key monitoring sites and CAMP were correlated with these annual summer NO<sub>2</sub> values. The resulting Pearson correlation coefficients are listed in Table 4-1. A large positive correlation implies that ozone is sensitive to increases or decreases in NO<sub>2</sub> and will decrease if NO<sub>2</sub> decreases. A large negative correlation indicates that ozone increases as NO<sub>2</sub> decreases. Values that indicate a moderate to strong positive correlation are highlighted in orange.

The CAMP site has a strong negative correlation and is highlighted in blue. The most likely cause for this is that there has been a reduction in the destruction of ozone by fresh emissions of NO as mobile sources of NO have decreased. The weather-corrected trend in fourth maximum ozone at the CAMP site in downtown Denver (see Figure 2-12) shows a steady, statistically significant increase in ozone with time, which is consistent with a long-term reduction of NO<sub>x</sub> emissions from mobile sources in downtown Denver. This indicates that ozone formation at the CAMP monitor is more VOC-limited and will be

subject to “NO<sub>x</sub> Disbenefits” (i.e., ozone increases in response to NO<sub>x</sub> emission reductions).

NREL has a weak correlation with area NO<sub>2</sub>, and FTCW and RFNO seem to have responded strongly to regional reductions in NO<sub>2</sub>. This indicates that ozone formation at the FTCW and RFNO is more NO<sub>x</sub>-limited with NO<sub>x</sub> emission reductions causing ozone reductions. NREL appears to be in a transitional area between more VOC- and NO<sub>x</sub>-limited ozone formation conditions. As NO<sub>x</sub> emissions are reduced, this transitional area and the areas of more NO<sub>x</sub>-limited ozone formation will move toward downtown Denver and NREL is expected to become the key ozone attainment monitoring site.

**Table 4-1. Pearson correlations between annual fourth maximum ozone and mean June through August OMI tropospheric NO<sub>2</sub>.**

Monitoring Site	Pearson Correlations between Fourth Maximum O <sub>3</sub> and Front Range OMI Tropospheric NO <sub>2</sub>
CAMP	-0.39
Chatfield	0.46
Fort Collins West	0.70
NREL	0.26
Rock Flats North	0.81

For the trend analysis, spatial averaging was performed using the Giovanni website tool over a bounding box defined by 106.25W, 38.75N, 103.75W 41.25 N which corresponds to the reanalysis grid cell for the region. Daily data were extracted for this region for June through August for 2006 – 2019, and non-negative daily values were averaged for each year. Note that each year had a minimum of 61 (of 92) days with good data included in the June-August average.

Figure 4-1 shows the trend in mean June through August OMI tropospheric NO<sub>2</sub> column totals for the 2.5 by 2.5 degree reanalysis grid cell that corresponds to DM/NFR NAA and much of the Front Range for 2006 through 2015. The regression line shows a statistically significant downward trend in regional NO<sub>2</sub>. Total column summer NO<sub>2</sub> declined by 27 percent between 2006 and 2019. In the current analysis, the relationship between NO<sub>2</sub> and 500 mb heights was not statistically significant so no corrections were made for weather.

The advantage of tracking trends for a larger region is that the impacts of possible errors or anomalies at the grid cell level in the OMI dataset are minimized. The disadvantage is that local changes affecting individual monitors cannot be tracked as easily. We did, however, use a spatial analysis tool on the Giovanni website to perform temporal averaging for June – August for 2015 and 2019 to assess differences in NO<sub>2</sub> for grid cells of 0.25 by 0.25 degrees.

Figure 4-2 shows the results of this analysis for the Front Range for 2015 and 2019. Grid cells shaded in grey are likely strongly influenced by satellite data noise, therefore the reader should focus on the colored grid cells only. In 2015, the red grid cells around Denver had NO<sub>2</sub> columns of 1.9 to 2.1 e+15 molecules/cm<sup>2</sup>, and the tropospheric columns throughout Weld County are generally in the 1.1 to 1.7 e+15 molecules/cm<sup>2</sup> range.

By 2019, NO<sub>2</sub> decreased substantially in the Denver area and increased substantially in northern Weld and Larimer Counties. The reason for this increase is unknown, but this increase is suspect. It is inconsistent with expected changes in emissions, known long-term sources, and trends in ozone at Fort Collins West. It is possible it is the result of a few high, anomalous days or that it reflects transport of emissions from Denver and the Platte Valley to the north at the satellite overpass time (~13:30 MST) during the summer of 2015.

Figure 4-3 shows the grid cell level ratios between 2019 and 2015 values. This map shows that 2019 values are 71 to 78 percent of 2015 values over much of the immediate Denver area and to the west into the foothills. On high ozone days, NO<sub>x</sub> emissions from the Cherokee power generation facility and mobile sources in Denver are routinely transported to the west, across the NREL monitor and up toward the Continental Divide. Evidence for this and the effects on ozone and its precursors were described in detail in the previous weather corrected trends report (CDPHE and RAQC, 2016). The reductions along this transport corridor might reflect the effects of substantial reductions in NO<sub>x</sub> emissions from Cherokee.

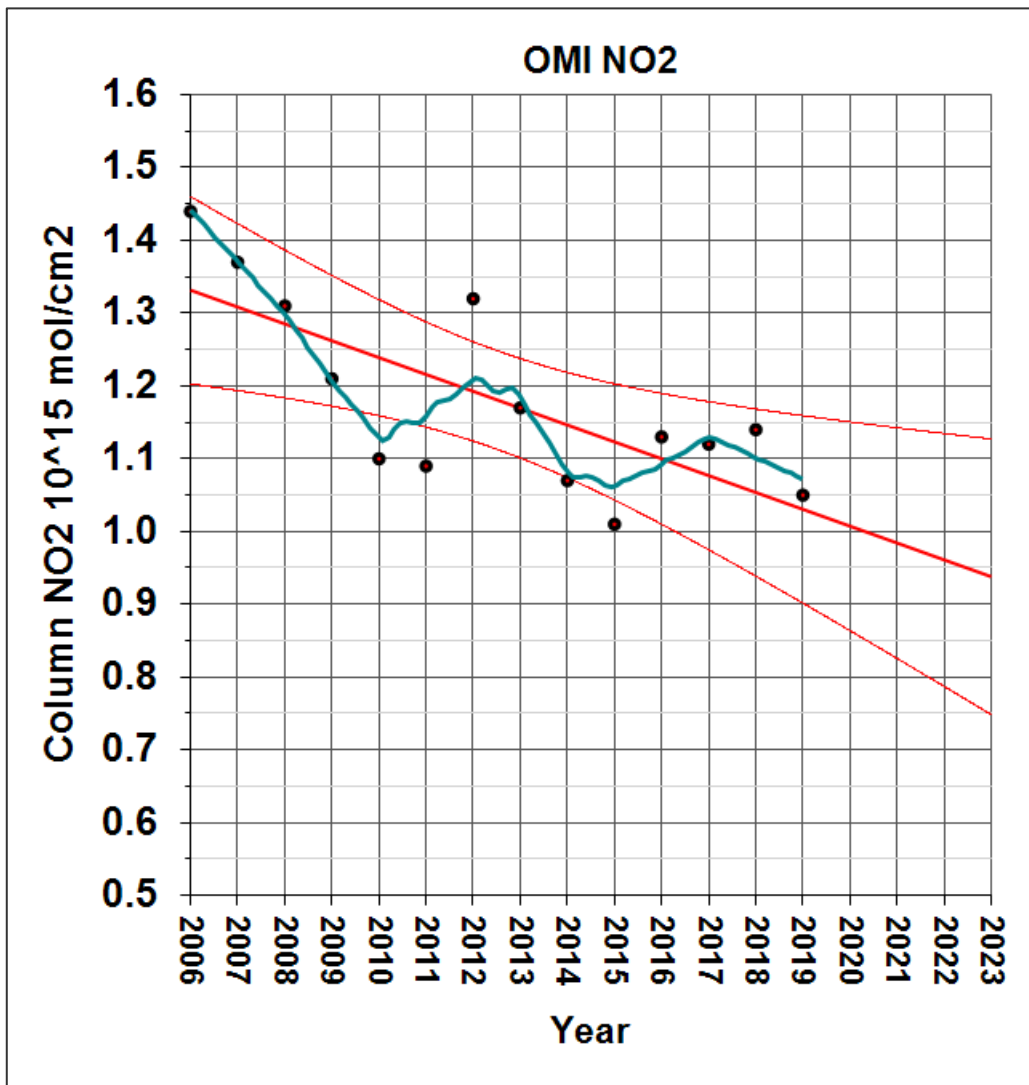
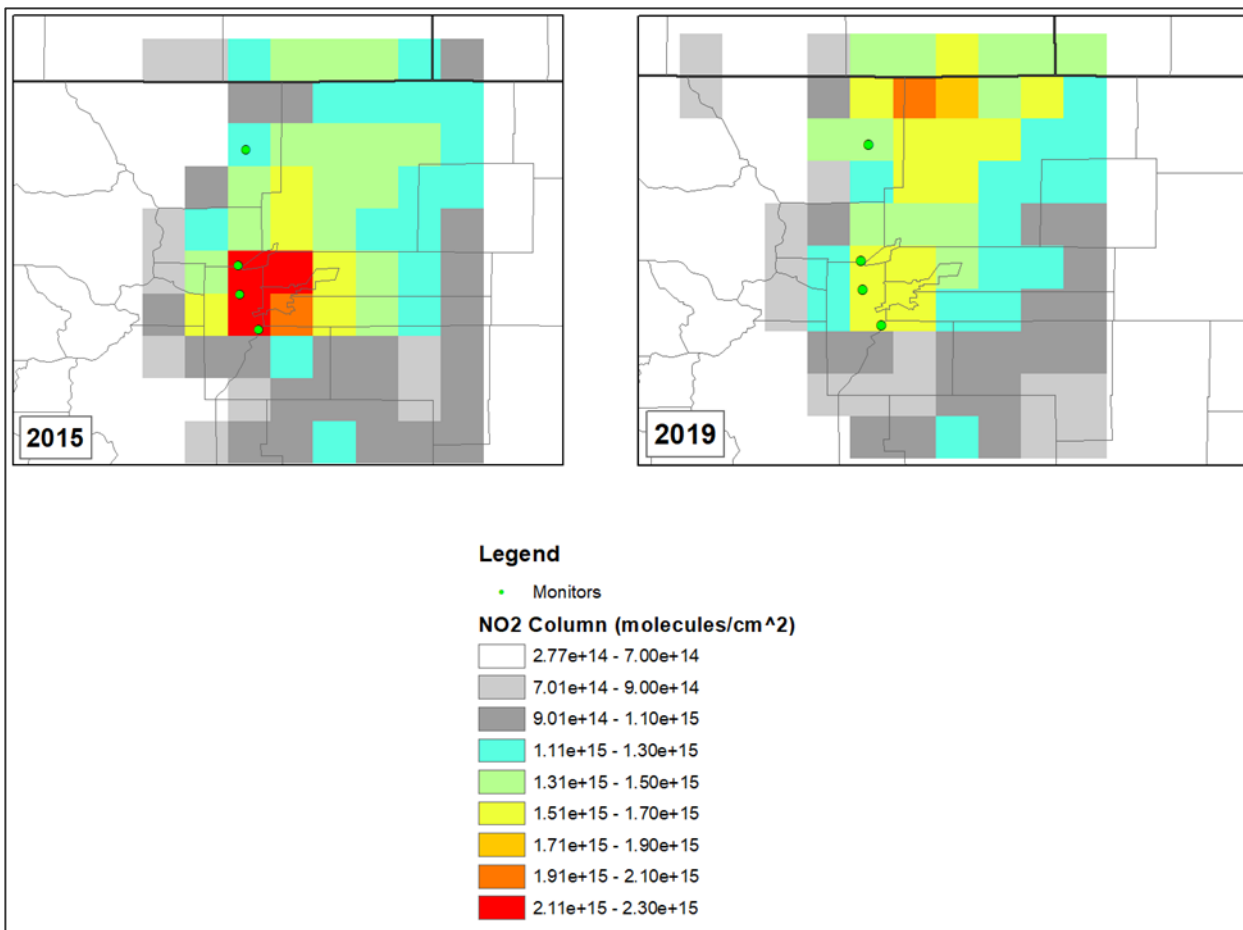


Figure 4-1. Trend in mean June through August OMI tropospheric column NO<sub>2</sub> (molecules per square centimeter) for the Denver/Front Range reanalysis grid cell. Red lines are the linear regression with confidence limits, the blue-green line is the LOESS smoothing curve.



**Figure 4-2. OMI version 003 Level 3 mean July through August tropospheric NO<sub>2</sub> data cloud- screened at 30% with a grid resolution of 0.25° by 0.25° for the Front Range for 2015 (left) and 2019 (right).**

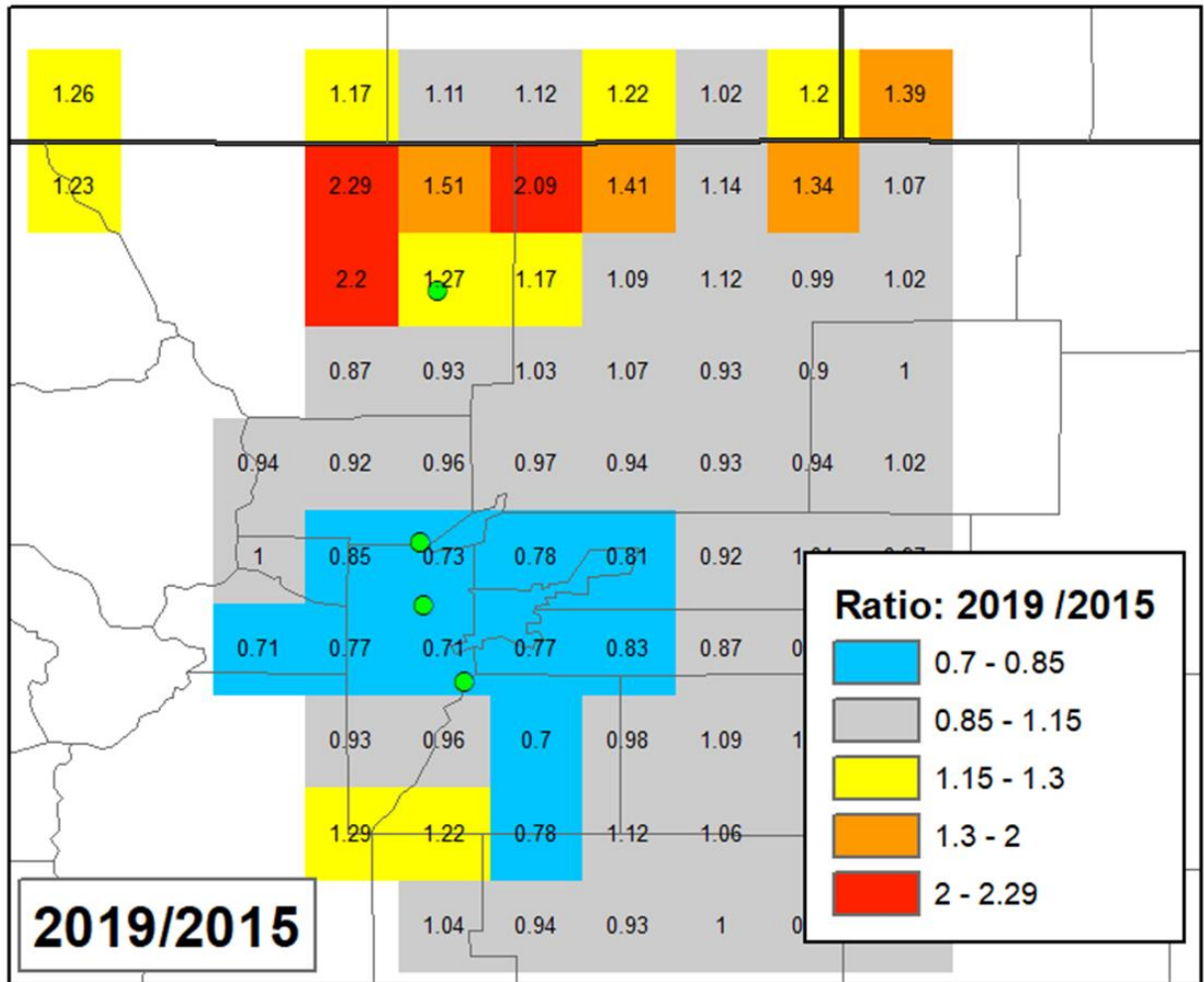


Figure 4-3. Ratios of 2019 to 2015 June through August OMI NO<sub>2</sub> for the Front Range region.

Figure 4-4 shows the total June through August NO<sub>x</sub> emissions in tons for the Cherokee electrical generating unit (EGU) immediately north of downtown Denver for 2011-2019. In 2015, Cherokee NO<sub>x</sub> emissions during June-August were roughly 1,200 tons and declined to about 200 tons by 2019. Table 4-2 shows Pearsons Correlations between weather corrected fourth highest MDA8 ozone (flagged events included) and June-August Cherokee NO<sub>x</sub> emissions (based on 2006-2019). NREL has the highest correlation at 0.84, followed by Rocky Flats North at 0.72. This is consistent with the conceptual model of thermally-drive upslope transport from Denver to the west on high-ozone days. These dramatic NO<sub>x</sub> emission reductions at Cherokee might be a major factor in the reductions in OMI NO<sub>2</sub> over and west of Denver since 2015 and the recent reductions in NREL ozone shown in Figure 2-10. NREL seems to have been more responsive to local NO<sub>x</sub> reductions than regional reductions.

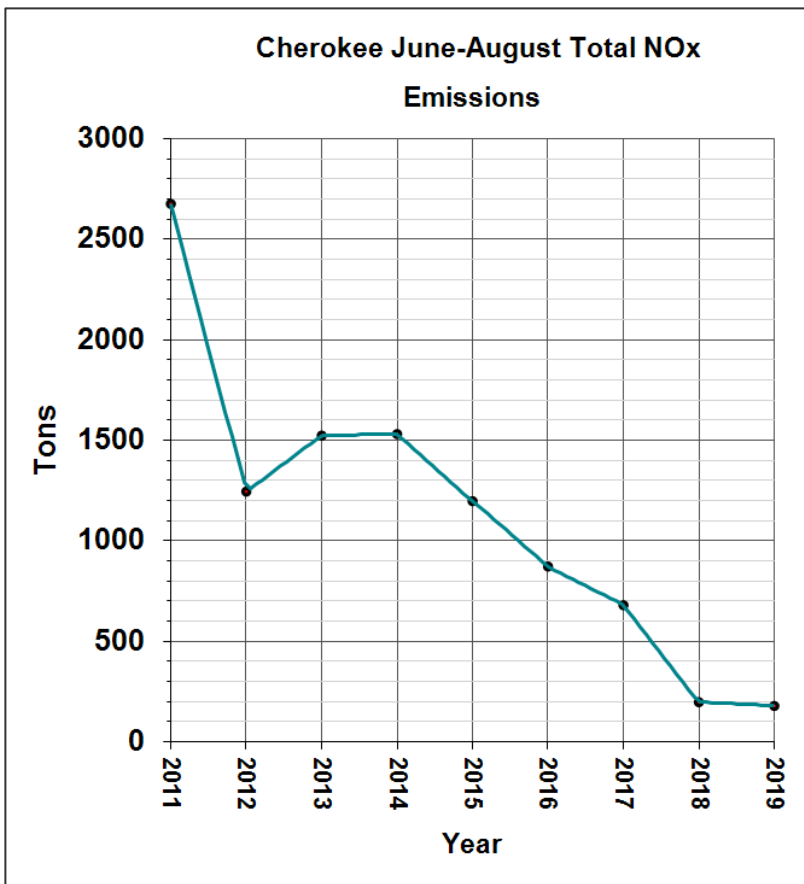


Figure 4-4. Cherokee EGU total NO<sub>x</sub> emissions in tons for June-August.

Table 4-2. Pearson's Correlations between weather corrected fourth highest MDA8 ozone (flagged events included) and June-August Cherokee NO<sub>x</sub> emissions (based on 2006-2019).

Monitoring Site	Pearson Correlations Between Fourth Maximum O <sub>3</sub> and Cherokee June-August Emissions
CAMP	-0.54
Chatfield	0.50
Fort Collins West	0.69
NREL	0.84
Rocky Flats North	0.72

## 5. SUMMARY

In summary, multiple lines of analysis support the projection of continued declines in ozone levels in response to reductions in emissions. These include analyses of trends in weather-corrected fourth highest MDA8 ozone, weather-corrected ozone standard exceedance counts, satellite-derived NO<sub>2</sub>, and the relationships between local ozone, NO<sub>2</sub>, and Cherokee NO<sub>x</sub> emissions. This analysis does not provide specific insights into the benefits of VOC reductions, but it is expected that these benefits are reflected in the downward trends in weather-corrected ozone. Weather corrected ozone concentrations with flagged events excluded suggest that Fort Collins West, Rocky Flats North, and NREL could each be below 70 ppb by 2023 under average weather conditions, while Chatfield would remain above 72 ppb. These projections do not account for any accelerated reductions in precursor emissions that might occur after the summer of 2019.

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