GEORGIA
DEPARTMENT OF NATURAL RESOURCES

ENVIRONMENTAL PROTECTION DIVISION

Final Report for Ozone Exceedances in the Metro Atlanta Area, Georgia during 2019-2021

Prepared by:
Planning and Support Program
Air Protection Branch
Environmental Protection Division

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Executive Summary

On October 1, 2015, the 8-hour ozone National Ambient Air Quality Standard (NAAQS) was lowered from 75 ppb to 70 ppb. The 2018-2020 and 2019-2021 ozone design values show that the Metro Atlanta area is no longer violating the 2015 ozone NAAQS. Even though ozone concentrations in Georgia have decreased over the past decades, the Metro Atlanta area (i.e., the Atlanta-Sandy Springs-Marietta metropolitan statistical area) still experiences ozone exceedances. An ozone exceedance is defined as a measured 8-hour average ozone concentration above 70 ppb. If the design value (3-year average of annual 4th highest daily maximum 8-hour average ozone concentrations) is over the ozone NAAQS level, EPA may reclassify the area as nonattainment. Therefore, understanding the ozone formation in the Metro Atlanta area will be critical to develop a plan to maintain its attainment status in the future.

Since 2016, the Data and Modeling Unit has developed an initial exceedance report for each ozone exceedance day.[1] These reports include a preliminary analyses of air quality, meteorological, and emission data to aid in determining the cause of the ozone exceedance. This final ozone exceedance report was developed for the Metro Atlanta area to evaluate the causes of the 2019-2021 ozone exceedances. This report consists of six parts: (1) an overview of ozone air quality in the Metro Atlanta area, (2) a trend of ozone air quality and meteorological conditions during 2011-2021, (3) ozone exceedances for 2019-2021, (4) NO_X emissions for 2019-2021, (5) multiple linear regression (MLR) analysis to understand the relationship between ozone and environmental variables, and (6) a summary of findings.

In summary, the following factors likely contributed to ozone exceedances in the Metro Atlanta area during 2019-2021:

1) High daily maximum air temperature on exceedance days;
2) Low relative humidity, cloud coverage, and wind speeds;
3) Local ozone formation at monitors inside the urban core due to local precursor emissions from the Atlanta urban core;
4) Local transport of ozone and precursors from the Atlanta urban core to monitors outside the urban core; and
5) NO_X emissions from Hartsfield-Jackson Atlanta International Airport and local on-road mobile sources (likely due to high traffic congestion, especially in the morning hours).

This final ozone exceedance report can be used to design air quality management plans in Georgia to prevent future ozone exceedances. The data in this report is in Eastern Standard Time (EST), unless otherwise denoted.

[1] Georgia DNR employees may download all initial ozone exceedance reports for 2019-2021 at Initial Ozone Exceedance Reports during 2019-2021. The general public may request a copy of these reports by sending an e-mail to Byeong.Kim@dnr.ga.gov.

List of Acronyms

AQI	Air Quality Index
AQS	Air Quality System
CAMD	Clean Air Markets Division
CASTNET	Clean Air Status and Trends Network
CO	Carbon Monoxide
ENSO	El Niño–Southern Oscillation
EPA	U.S. Environmental Protection Agency
EPD	Environmental Protection Division
GIF	Graphics Interchange Format
HCHO	Formaldehyde
HJAIA	Hartsfield-Jackson Atlanta International Airport
HYSPLIT	Hybrid Single Particle Lagrangian Integrated Trajectory
IDL	Interactive Data Language
LIDAR	Light Detection and Ranging
LT	Local Time
MAE	Mean Absolute Error
MB	Mean Bias
mb	millibar (=10^{-3} bar)
MDA8O3	Maximum Daily 8-hour Average Ozone Concentrations
MLR	Multiple Linear Regression
MSAs	Metropolitan Statistical Areas
NAAQS	National Ambient Air Quality Standards
NAM	North American Mesoscale
NCEI	National Centers for Environmental Information
NEI	National Emissions Inventory
NMB	Normalized Mean Bias
NME	Normalized Mean Error
NOAA	National Oceanic and Atmospheric Administration
NO_X	Oxides of Nitrogen
OMI	Ozone Monitoring Instrument
PAMS	Photochemical Assessment Monitoring Stations
PBL	Planetary Boundary Layer
QA	Quality Assurance
RH	Relative Humidity
RMSE	Root Mean Square Error
RWC	Reactivity-weighted concentrations
VOC	Volatile Organic Compounds

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1. Introduction

Ground-level ozone pollution can impair lung function and cardiovascular health. Ground-level ozone is formed in the atmosphere by chemical reactions of oxides of nitrogen (NO_X) and volatile organic compounds (VOCs) in the presence of sunlight. NO_X emissions are primarily from the combustion of fuels. Sources of VOCs include fuel combustion, fuel evaporation, paints, solvents, and vegetation. On October 1, 2015, the U.S. Environmental Protection Agency (EPA) lowered the National Ambient Air Quality Standards (NAAQS) for ground-level ozone from 75 ppb (2008 ozone NAAQS) to 70 ppb (2015 ozone NAAQS) to better protect public health and welfare.

Ozone concentrations in Georgia have decreased over the years (Figure 1) in various metropolitan statistical areas (MSAs). The Metro Atlanta area (i.e., the Atlanta-Sandy Springs-Marietta MSA) was the only area in Georgia designated nonattainment for the 2008 ozone NAAQS. This area was redesignated to attainment in June 2017. On June 4, 2018[2], EPA designated seven counties (Bartow, Clayton, Cobb, DeKalb, Fulton, Gwinnett, and Henry) as nonattainment areas for the 2015 ozone NAAQS. Currently, no monitors in the Metro Atlanta area are violating the 2015 ozone NAAQS.

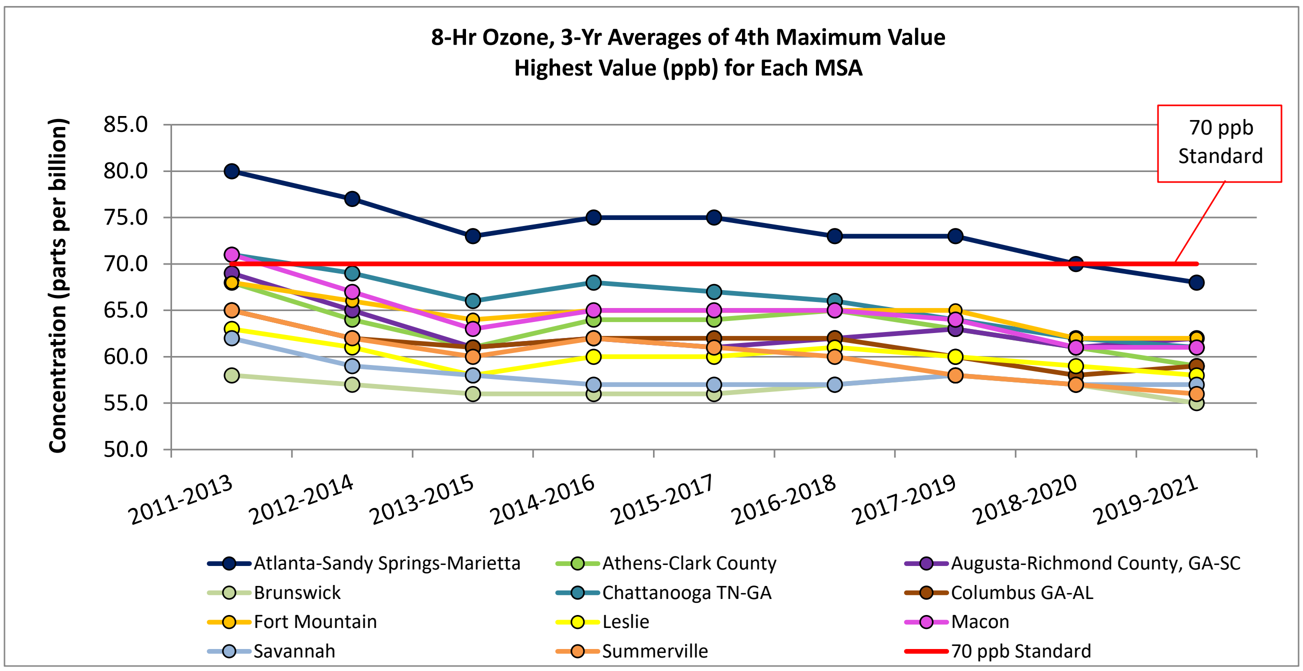

Figure 1. Trend of ozone design values by various MSAs in Georgia.

An "exceedance" is defined as a measured *daily maximum 8-hour average ozone concentration* ("MDA8O3") above 70 ppb. In 2019, three MSAs (Atlanta-Sandy Springs-Marietta, Macon, and Augusta MSAs) experienced ozone exceedances. In 2020, one MSA (Atlanta-Sandy Springs-Marietta MSA) experienced an ozone exceedance. In 2021, two MSAs (Atlanta-Sandy Springs-Marietta and Macon MSAs) experienced ozone exceedances. If the ozone design value (3-year average of annual 4th highest MDA8O3) is over the ozone NAAQS level, EPA may classify the area as nonattainment.

[2] The redesignation was effective August 3, 2018.

In the Metro Atlanta area, eight EPD-operated ozone monitors and one EPA-operated monitor (EPA CASTNET) measure hourly ozone concentrations. Figure 2 shows the location of these nine monitors and the number of ozone exceedance days during 2019-2021. During 2019-2021, the most frequent ozone exceedances occurred at the United Ave. monitor located in downtown Atlanta and the McDonough monitor in Henry County.

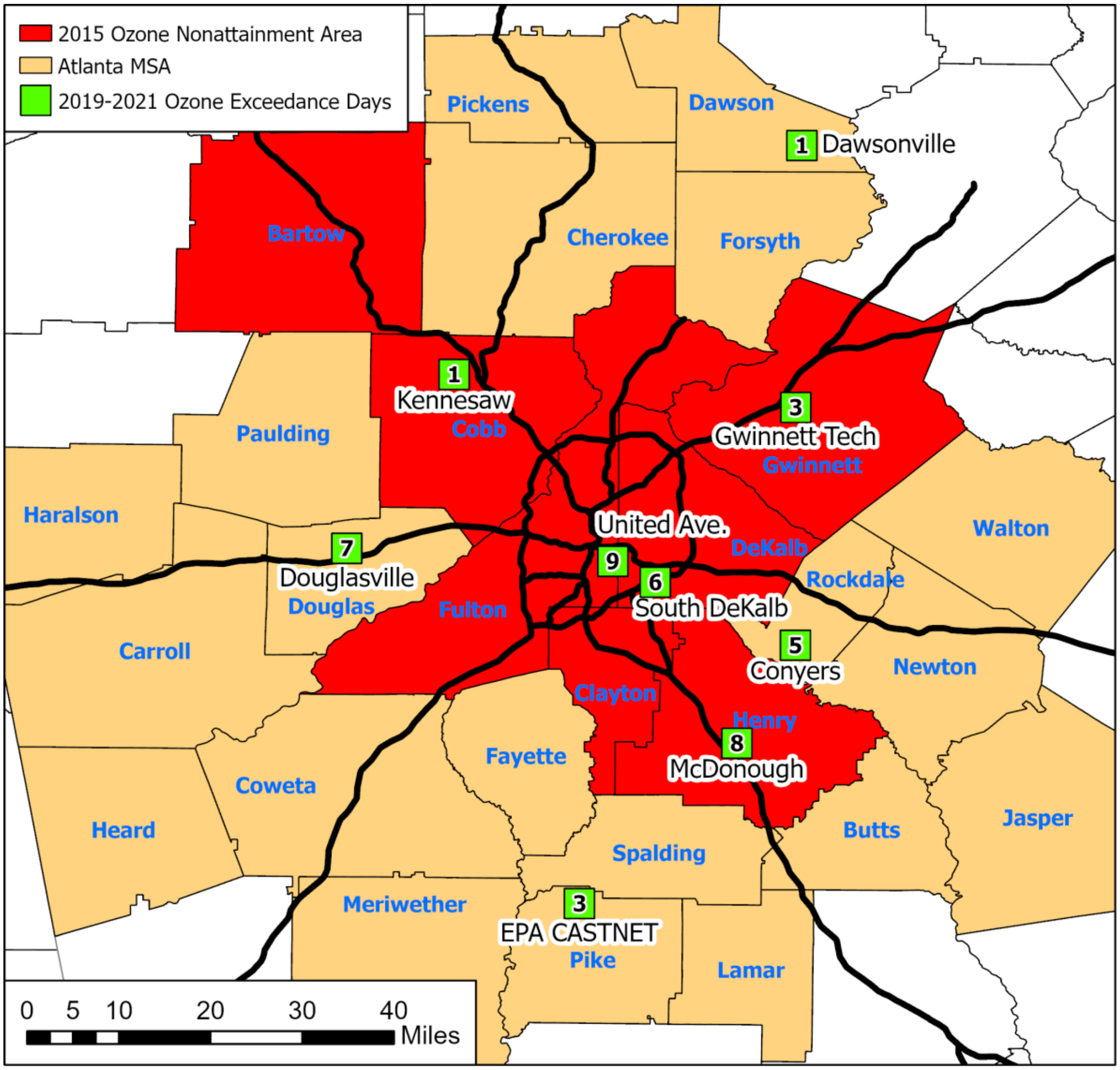

Figure 2. Locations of ozone monitors and the number of ozone exceedance days in the Metro Atlanta area during 2019-2021.

This final ozone exceedance report was developed for the Metro Atlanta area to evaluate causes of the 2019-2021 ozone exceedances. This report consists of six parts: (1) an overview of ozone air quality in the Metro Atlanta area, (2) a trend of ozone air quality and meteorological conditions during 2011-2021; (3) ozone exceedances for 2019-2021; (4) NO_X emissions for 2019-2021; and (5) multiple linear regression (MLR) analysis to understand the relationship between ozone and environmental variables, and (6) a summary of findings. The data in this report is in Eastern Standard Time (EST), unless otherwise denoted.

2. Long-term Trend Analysis for Ozone and Meteorology in the Metro Atlanta Area

2.1. Ozone Exceedance Trends in the Metro Atlanta Area (2011-2021)

Ozone design values (Table 1 and Figure 3) and annual 4th highest daily maximum 8-hour average ozone concentrations (Table 2 and Figure 4) for nine ozone monitors in the Metro Atlanta area during 2011-2021 show downward trends. Currently, the Metro Atlanta area has no monitors with design values above 70 ppb. No monitors had a 4th highest concentration above 70 ppb in 2020 and 2021 while five monitors had their 4th highest concentrations above 70 ppb in 2019.

The annual maximum, mean, and median MDA8O3 values during ozone seasons[3] in 2011-2021 shows the inter-annual variability with a downward trend through the years (Figure 5). The annual mean MDA8O3 in 2011 was highest at 59.4 ppb and decreased to the lowest in 2020 at 42.8 ppb. The annual mean MDA8O3 increased slightly to 46.5 ppb in 2021. This downward trend generally coincides with NO_X (Figure 6) and VOC (Figure 7) emissions reductions in Georgia over the same period of time. However, the minimum MDA8O3 stayed very constant around 20 ppb although the maximum MDA8O3 decreased throughout the years. The number of exceedance days during the 2011-2021 ozone seasons shows a decreasing pattern similar to the maximum MDA8O3 values. We see a relatively large number of ozone days above 70 ppb in 2011, 2016, and 2019 compared with their adjacent years.

The monthly average ozone exceedance days and percentage of exceedance occurring in April to October are summarized by different time periods during 2011-2021 in the Metro Atlanta area (Figure 8). Typically, more than 70% of the ozone exceedances occur during June-September when temperatures are higher and sunlight is more intense than April and October. However, during 2019-2021, more exceedances occurred in April and October while less exceedances occurred in July compared with those in 2011-2018. Also, the weekly patterns of ozone exceedances were investigated (Figure 9). In recent years (i.e., 2019-2021), relatively more ozone exceedances occurred on Monday, Tuesday, and Friday than 2011-2018. No exceedances were observed on Sundays during 2019-2021.

To investigate the effects of “carry-over” (ozone concentrations on the days leading up to an ozone exceedance), the mean ozone increases on exceedance days were calculated by subtracting ozone concentrations on one day or two days before exceedance days/events from ozone concentrations on exceedance days (Figure 10).[4] The larger the ozone increases are, the less the impacts of carry-over ozone are on exceedances. In 2019, the average increased ozone concentration on two days and one day before exceedance days was similar to the average value during 2011-2021. The maximum ozone increase from two days before the exceedance day was 35.0 ppb in 2020, while the maximum ozone increase from one day before the exceedance day was 18.7 ppb in 2021. This analysis result indicates that ozone exceedances in the Metro Atlanta will likely be single-day events in the future although further studies are warrantied once 2022 ozone data are collected.

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[3] Ozone season in Georgia is March 1 – October 31. However, for the purpose of this report, we defined April 1 – October 30 as the ozone season in the Metro Atlanta area unless otherwise noted.

[4] MDA8O3 values used in Figure 10 are annual averaged values of daily maximum MDA8O3 values among 9 monitors in the Metro Atlanta area on the day before an exceedance day, on the exceedance day, and the day after the exceedance day, respectively.

Table 1. Design values for nine ozone monitors in the Metro Atlanta area during 2011-2021.

AQS	Site Name	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
13-067-0003	Kennesaw	**78**	**77**	**73**	-	-	-	67	66	65	62	61
13-085-0001	Dawsonville	68	67	64	64	64	65	65	65	64	61	60
13-089-0002	South DeKalb	**77**	**80**	**75**	**72**	67	**71**	**71**	69	69	67	67
13-097-0004	Douglasville	**74**	**75**	**71**	67	66	68	69	67	67	64	66
13-121-0055	United Avenue	**80**	**83**	**80**	**76**	**73**	**75**	**75**	**73**	**73**	70	68
13-135-0002	Gwinnett	**75**	**78**	**77**	**72**	69	**72**	**71**	69	66	66	66
13-151-0002	McDonough	**78**	**82**	**80**	**77**	**71**	**74**	**71**	**71**	70	67	66
13-231-9991	EPA CASTNET	-	-	**72**	69	66	68	67	-	-	-	61
13-247-0001	Conyers	**75**	**79**	**77**	**77**	**72**	**74**	69	70	68	67	65

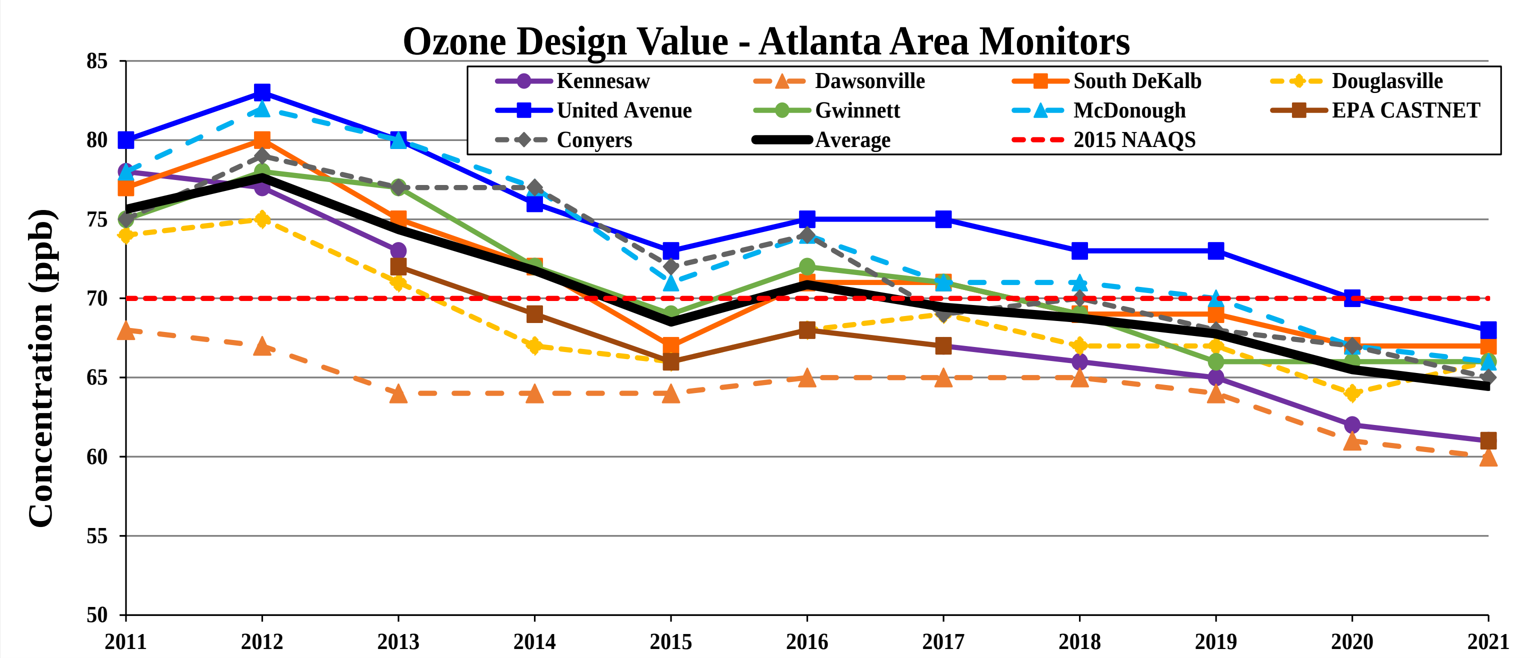

Figure 3. Ozone design values for nine ozone monitors in the Metro Atlanta area during 2011-2021.

Table 2. Annual 4th highest daily maximum 8-hour average ozone concentrations (ppb) for nine ozone monitors in the Metro Atlanta area during 2011-2021.

AQS	Site Name	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
13-067-0003	Kennesaw	**79**	**75**	67	63	66	70	65	65	67	56	62
13-085-0001	Dawsonville	66	63	63	66	63	67	65	65	62	57	61
13-089-0002	South DeKalb	**80**	**85**	62	70	**71**	**74**	68	67	**73**	61	67
13-097-0004	Douglasville	**78**	**73**	63	65	70	**71**	66	64	**72**	56	70
13-121-0055	United Avenue	**84**	**87**	69	**73**	**77**	**75**	**74**	**72**	**75**	63	66
13-135-0002	Gwinnett	**82**	**80**	69	68	**71**	**78**	65	65	68	66	65
13-151-0002	McDonough	**82**	**88**	70	**75**	70	**78**	67	69	**75**	58	66
13-231-9991	EPA CASTNET	**75**	**77**	64	66	68	**71**	62	-	68	54	61
13-247-0001	Conyers	**81**	**81**	**71**	**79**	68	**76**	65	69	**72**	60	63

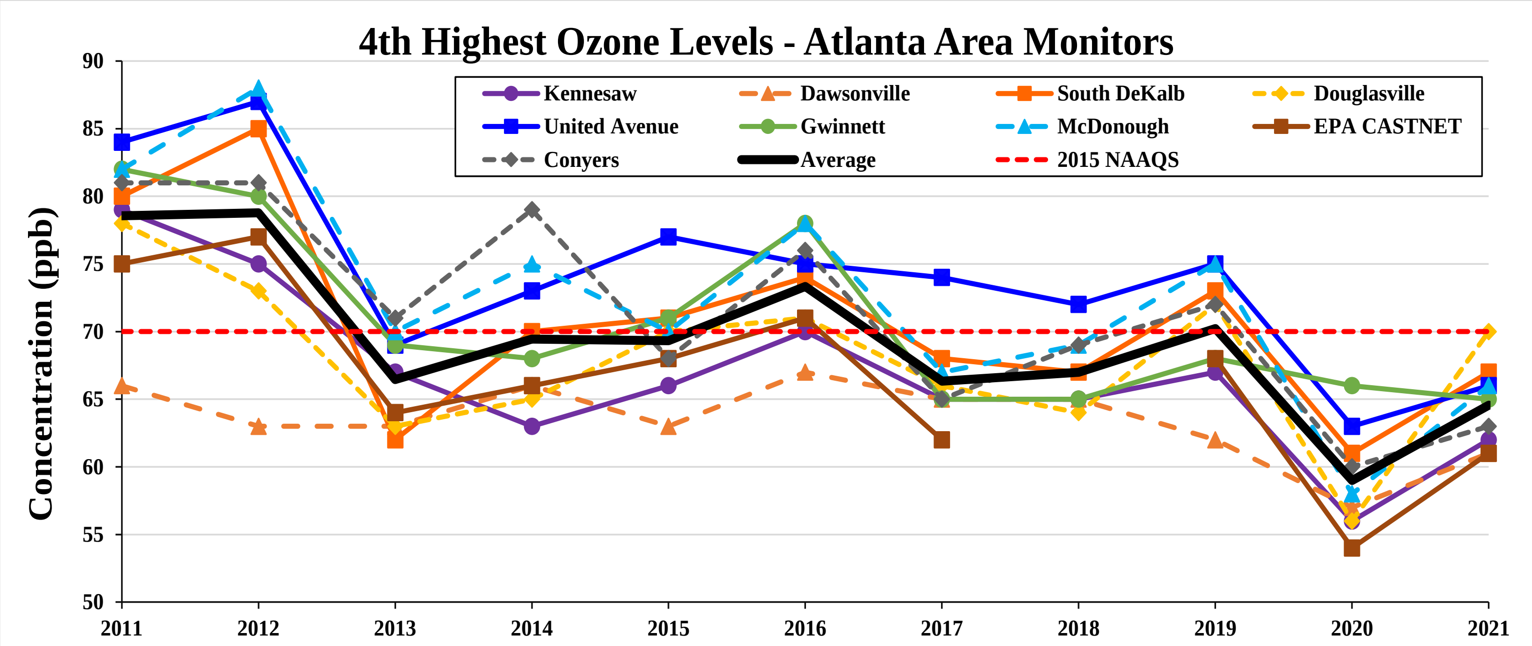

Figure 4. Annual 4th highest daily maximum 8-hour average ozone concentrations (ppb) for nine ozone monitors in the Metro Atlanta area during 2011-2021.

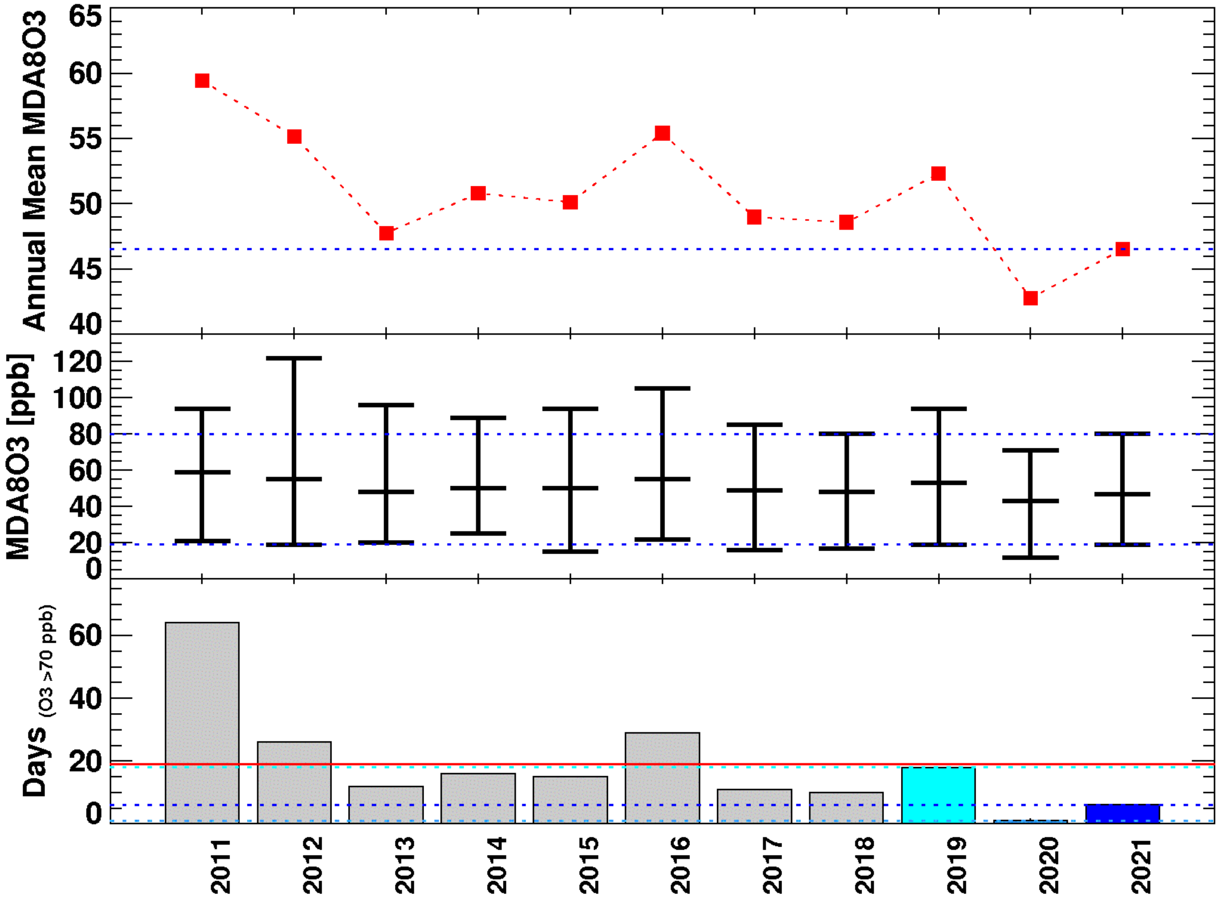

Figure 5. Annual Mean MDA8O3 concentrations (the top panel); minimum (bottom bar), median (middle bar), and maximum (top bar) MDA8O3 concentrations (the middle panel); and the number of ozone exceedance days (the bottom panel) from April to October in 2011-2021 in the Metro Atlanta area. 2019, 2020, and 2021 values are highlighted in cyan, light blue, and blue, and drawn in cyan, light blue, and blue dotted lines. The red solid line is the average for 2011-2021.

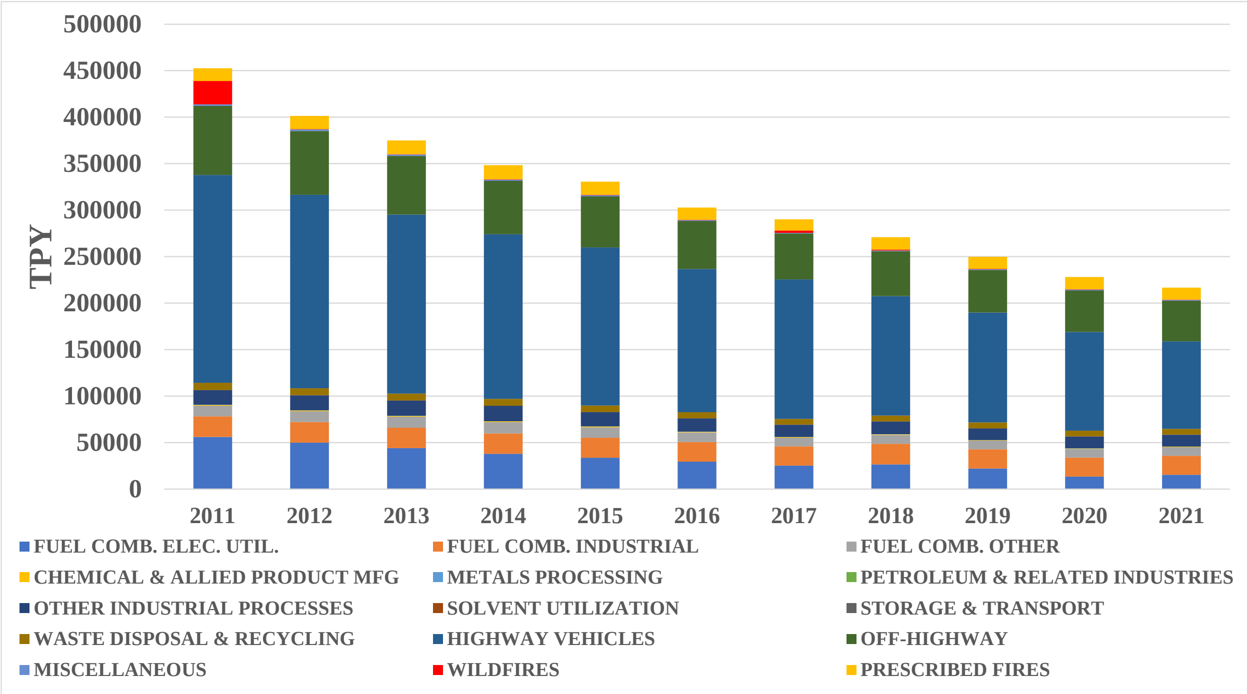

Figure 6. Georgia NO_X emission trends by source sectors during 2011-2021.

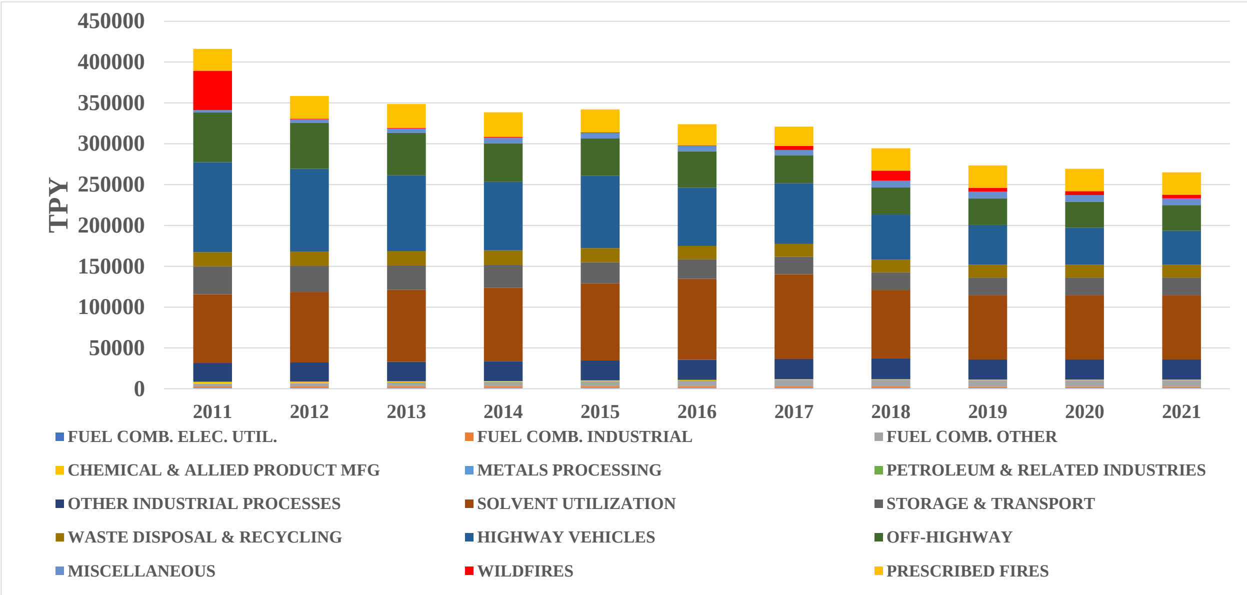

Figure 7. Georgia VOCs emission trends by source sectors during 2011-2021.

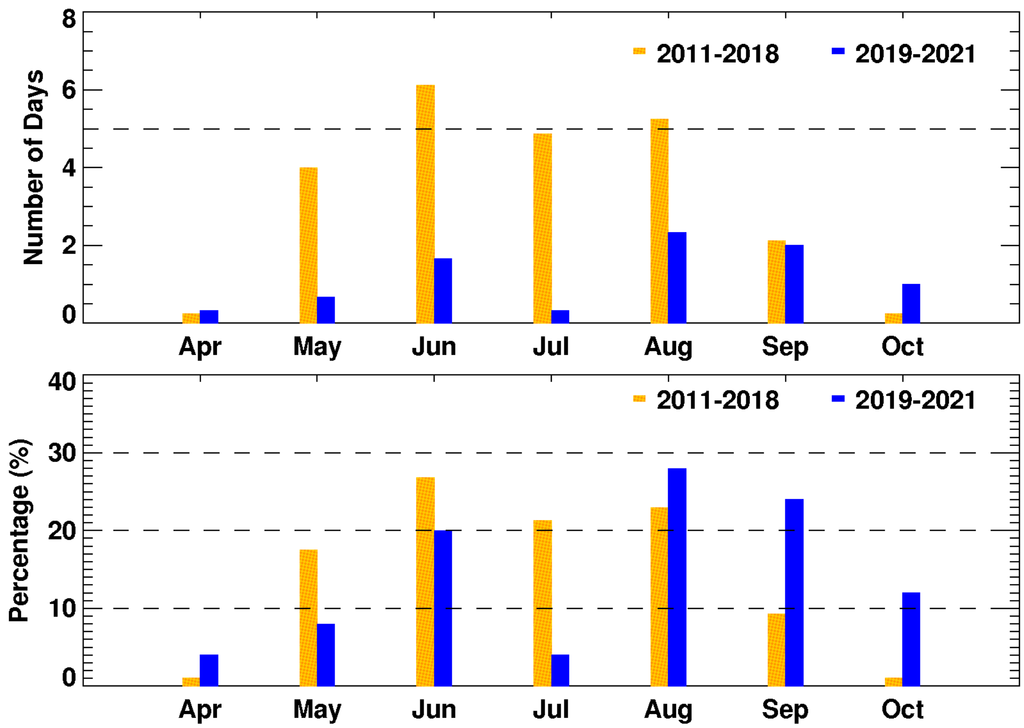

Figure 8. Monthly average number of ozone exceedance days (top) and percentage of exceedances occurring in that month (bottom) in ozone season by different time periods during 2011-2021 in the Metro Atlanta area.

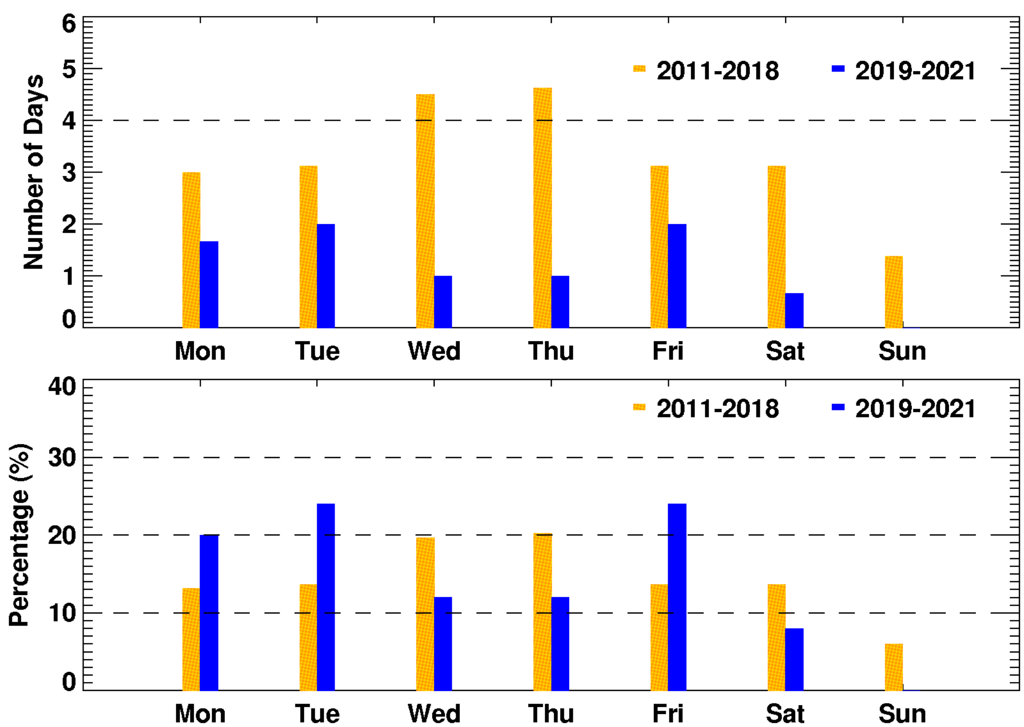

Figure 9. The number (top) and percentage (bottom) of ozone exceedance days by days of week for different periods during 2011-2021 in the Metro Atlanta area.

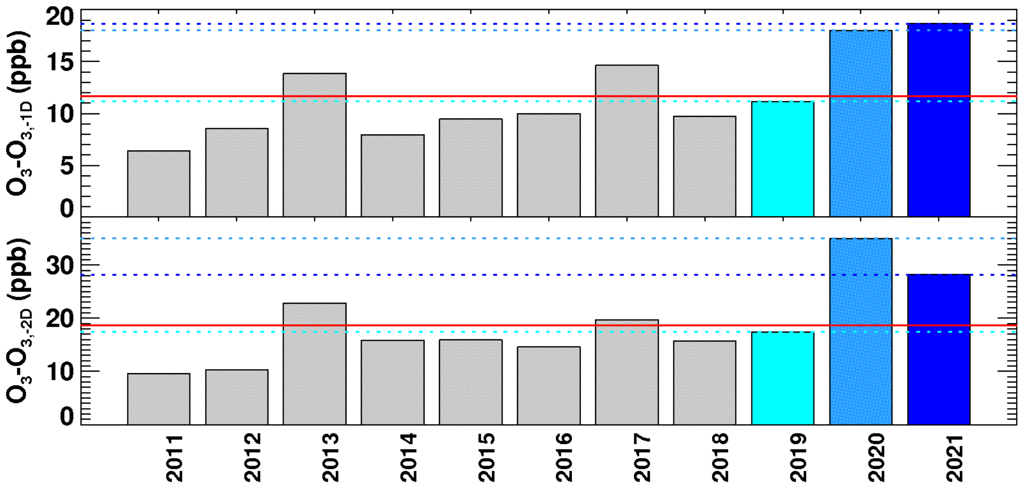

Figure 10. The mean ozone increases (ppb) from one day before (top) and two days before (bottom) the ozone exceedance days during 2011-2021 in the Metro Atlanta area. 2019, 2020, and 2021 values are highlighted in cyan, light blue, and blue and drawn in cyan, light blue, and blue dotted lines, respectively. The red solid line is the average for 2011-2021.

2.3. Meteorological Conditions in the Metro Atlanta Area (2011-2021)

Trends of meteorological conditions in Atlanta during 2011-2021 were analyzed using meteorological observations at the Hartsfield-Jackson Atlanta International Airport (HJAIA) (Table 3) downloaded from Iowa Environmental Mesonet[5]. The observational intervals varied from one hour to several minutes depending on variables.

Table 3. Observed meteorological variables at the Hartsfield-Jackson Atlanta International Airport (HJAIA).

Variables	Definition	Unit
tmpf	Air Temperature, typically @ 2 meters	degree of Fahrenheit
dwpf	Dew Point Temperature, typically @ 2 meters	degree of Fahrenheit
relh	Relative Humidity	%
drct	Wind Direction	degree from north
sknt	Wind Speed	knots
p01i	One-hour precipitation for the period from the observation time to the time of the previous hourly precipitation reset.	inches
alti	Pressure altimeter	inches
mslp	Sea Level Pressure	millibar
vsby	Visibility	miles
gust	Wind Gust	knots
skyc1	Sky Level 1 Cloud Coverage	%
skyc2	Sky Level 2 Cloud Coverage	%
skyc3	Sky Level 3 Cloud Coverage	%
skyc4	Sky Level 4 Cloud Coverage	%

Mean meteorological conditions in ozone season were calculated for each year (Figure 11). Most variables have some interannual variations. During 2019-2021, AM and PM cloud coverages (defined as the percentage of sky covered by clouds) were less than the 2011-2021 average cloud. T_{max} in 2019 was higher than the 2011-2021 average while T_{max} in 2020 and 2021 was lower. Morning and afternoon relative humidity values in 2019 were lower than 2011-2021 averages while they were higher in 2020 and 2021. Other meteorological conditions in 2019-2021 are similar to the 2011-2021 average conditions.

Figure 5 indicates that 2011, 2012, 2016, and 2019 were the four years with the highest number of ozone exceedance days. Figure 11 indicates that 2011, 2012, 2016, and 2019 had significantly lower morning and afternoon relative humidity values and moderately higher T_{max} values compared to the other years in the figure. This highlights the importance of relative humidity and temperate on ozone formation.

[5] https://mesonet.agron.iastate.edu/request/download.phtml?network=GA_ASOS

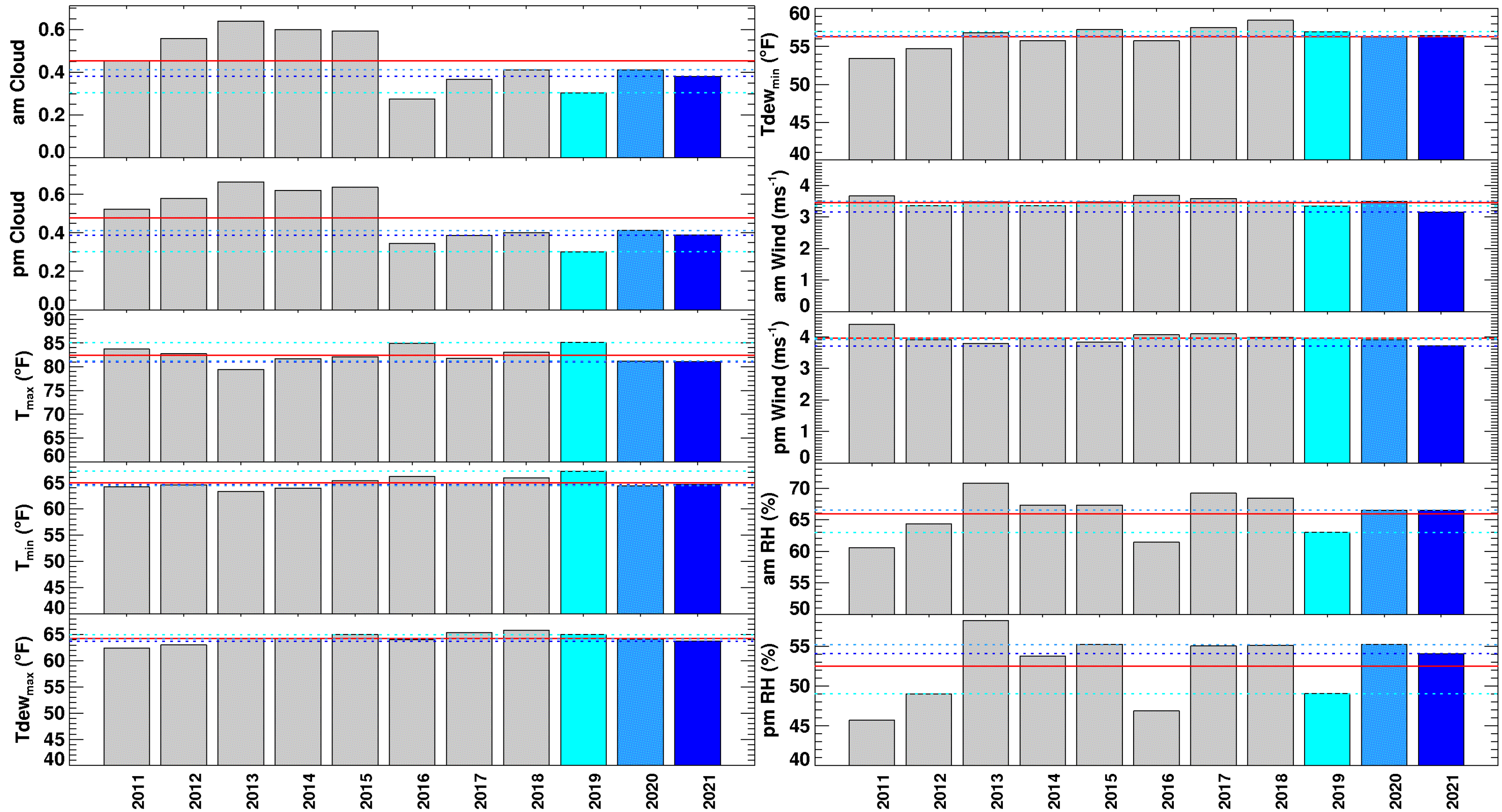

Figure 11. Atlanta ozone season mean meteorological conditions during 2011-2021. 2019, 2020, and 2021 values are highlighted in cyan, light blue, and blue and represented by the cyan, light blue, and blue dotted lines, respectively. 2011-2021 average values are represented by the red solid line to facilitate comparison.

3. Ozone Exceedances in 2019-2021

3.1. Frequency of Ozone Exceedances

As shown in Table 4, the nine ozone monitors in the Metro Atlanta area had 18 ozone exceedance days in 2019, one ozone exceedance day in 2020, and six ozone exceedance days in 2021. In 2019, there were multiple exceedance days when ozone exceedances occurred at more than one monitor on the same day: two exceedance days (September 9 and October 3) at four monitors, four exceedance days (June 3, August 17, September 13, and September 17) at three monitors, and two exceedance days (June 14 and August 9) at two monitors. For the other 10 exceedance days, the ozone exceedances only occurred at one monitor for each day. In 2020, the ozone exceedance only occurred at one monitor on May 2. In 2021, exceedances at two monitors occurred on two days (May 24 and August 13) while the ozone exceedances only occurred at one monitor on the other four exceedance days.

Table 4. Ozone concentrations (ppb) for nine ozone monitors in the Metro Atlanta area on exceedances days during 2019-2021.

Year	Month	Day	Day of Week	United Ave.	McDonough	Dawsonville	South DeKalb	Conyers	Douglasville	EPA CASTNET	Gwinnett Tech	Kennesaw	Number of Exceedance Monitors
2019	**April**	17	Wednesday	62	52	**78**	59	56	56	55	68	62	1
2019	**June**	3	Monday	**73**	**79**	55	68	**73**	57	68	60	62	3
2019	**June**	4	Tuesday	62	56	53	57	57	**72**	61	60	59	1
2019	**June**	14	Friday	**81**	66	55	**74**	62	58	58	63	67	2
2019	**July**	2	Tuesday	65	**75**	39	62	67	51	49	52	52	1
2019	**August**	9	Friday	61	**71**	38	61	**72**	43	52	52	50	2
2019	**August**	14	Wednesday	64	**74**	30	62	65	45	54	49	49	1
2019	**August**	16	Friday	68	**77**	42	67	69	54	57	55	59	1
2019	**August**	17	Saturday	70	**85**	40	**73**	**79**	54	68	62	50	3
2019	**September**	9	Monday	**94**	64	44	**89**	68	**78**	61	**74**	67	4
2019	**September**	12	Thursday	69	57	47	63	64	**73**	63	61	56	1
2019	**September**	13	Friday	**71**	52	51	60	59	**73**	59	68	**76**	3
2019	**September**	16	Monday	63	58	40	62	61	59	**76**	51	49	1
2019	**September**	17	Tuesday	**71**	**72**	45	67	**73**	55	62	55	60	3
2019	**September**	30	Monday	**75**	55	43	70	50	49	60	57	55	1
2019	**October**	1	Tuesday	65	50	47	57	54	**71**	57	57	50	1
2019	**October**	3	Thursday	**76**	68	45	**73**	**72**	69	**84**	61	13	4
2019	**October**	4	Friday	66	70	44	65	66	54	**79**	59	49	1
2020	**May**	2	Saturday	69	61	62	66	61	55	59	**71**	56	1
2021	**May**	24	Monday	**80**	64	52	**76**	62	59	58	63	62	2
2021	**June**	15	Tuesday	65	**74**	47	63	68	58	64	58	58	1
2021	**June**	23	Wednesday	50	43	36	45	42	**71**	50	39	53	1
2021	**August**	12	Thursday	**75**	48	33	67	57	40	50	49	58	1
2021	**August**	13	Friday	66	-	43	**74**	62	50	46	**73**	48	2
2021	**August**	24	Tuesday	-	40	44	48	44	**71**	47	54	52	1

The number of ozone exceedance days by month during 2019-2021 are summarized in Table 5. Most exceedances occurred in the months of June, August, and September during 2019-2021. The July exceedance at the McDonough monitor was in 2019.

Table 5. Month-by-month summary of 2019-2021 ozone exceedances for nine ozone monitors in the Metro Atlanta area.

ID	Site Name	April	May	June	July	August	September	October	Total
131210055	United Ave.		1	2		1	4	1	**9**
131510002	McDonough			2	1	4	1		**8**
130970004	Douglasville			2		1	3	1	**7**
131350002	South DeKalb		1	1		2	1	1	**6**
132470001	Conyers			1		2	1	1	**5**
132319991	EPA CASTNET						1	2	**3**
131350002	Gwinnett Tech		1			1	1		**3**
130850001	Dawsonville	1							**1**
130670003	Kennesaw						1		**1**
Total		**1**	**3**	**8**	**1**	**11**	**13**	**6**	**43**

The day-specific meteorological conditions were investigated further for the 25 ozone exceedance days in 2019-2021. The relative humidity, cloud fractions, wind speeds in the morning and afternoon, and daily maximum and minimum temperatures on the day before and after each exceedance day/event are compared to those on the exceedance day (Figure 12). For the days without observations, the data from two days before or after are used. Continuous exceedances lasting more than one day are considered as one event. In general, the ozone exceedance days feature lower relative humidity, less cloud coverage, lower wind speeds, and higher daily max temperatures compared to non-exceedance days.

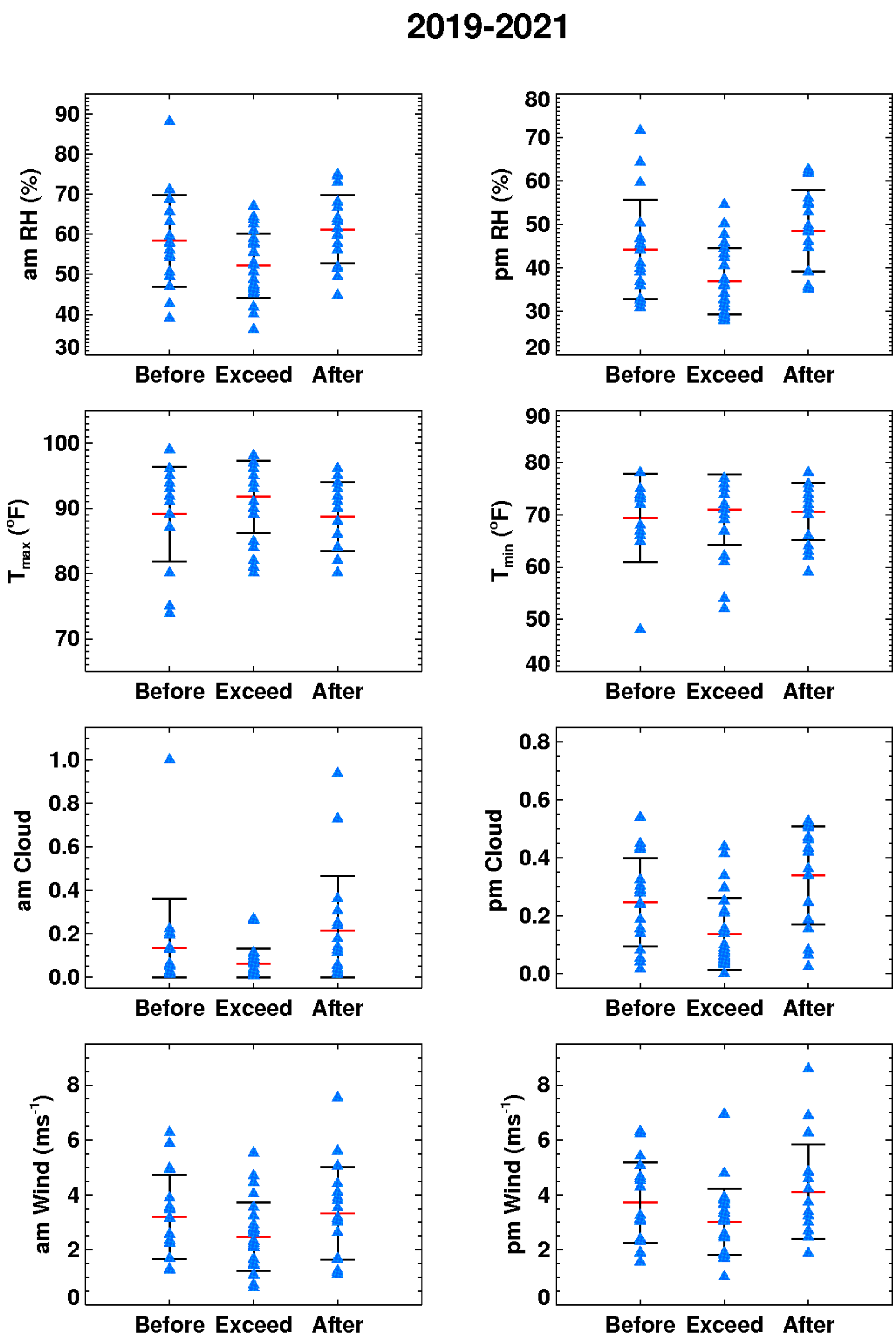

Figure 12. Comparisons of meteorological variables in 2019, 2020, and 2021 on the ozone exceedance days/events and the day before/after the exceedance. The red bar is the mean, and the upper and lower bars (black) represent the standard deviations. All samples are shown (blue triangles).

3.2. Animation of Ozone and Wind Conditions on Selected Exceedance Days

Animation of 5-minute ozone concentrations and wind conditions were developed for the 25 ozone exceedance days during 2019-2021 over 4-km grids covering the Metro Atlanta area in order to further understand the formation and transport of ozone. The 5-minute ozone concentrations were calculated using 1-minute observations at ozone monitors collected by the Ambient Monitoring Program. The 5-minute surface wind conditions were simulated using the Weather Research and Forecasting (WRF) model (v3.9.1.1). WRF was first run for the 12-km domain over the southeastern United States (69×68 grids) and then run for the 4-km nested domain over Georgia (148×145 grids) (Figure 13) with the NAM analysis meteorological data downloaded from NOAA FTP server[6]. The WRF configuration for physics and dynamics was the same as EPA's 2016 WRF modeling setup. Thirty-five (35) vertical layers extending up to 50 mb were used. The simulation episode was 36 hours for each exceedance day with 6 spin-up hours. The 5-minute ozone data at monitors were further processed to 4-km WRF grids using Kriging 2D interpolation method. For each exceedance day, sixteen hourly ozone and wind condition plots (7:00 AM to 10:00 PM) were developed. The animations dynamically demonstrate the Atlanta urban core as the origin of most high ozone events.

For ozone exceedances inside the Atlanta urban core, wind speeds were generally low (e.g., Figure 14). For ozone exceedances that occurred outside of the Atlanta urban core, the general pattern is that wind blew from the urban core to the exceedance monitor (e.g., Figure 15). Appendix A contains ozone-wind plots for all other exceedances during 2019-2021.

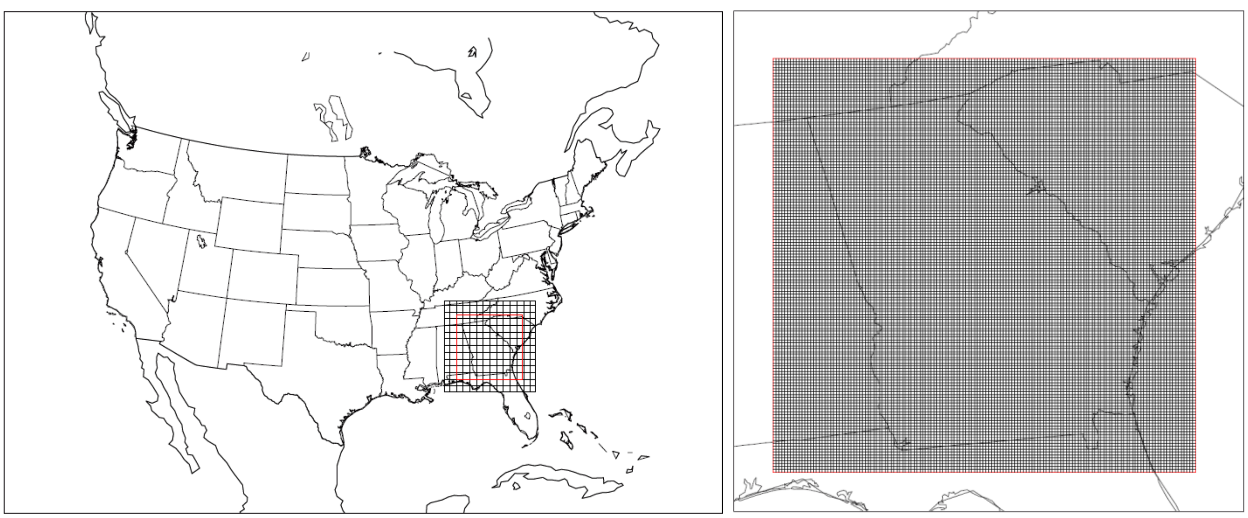

Figure 13. WRF 12-km domain over the southeastern United States (left) and 4-km nested domain over Georgia (right).

[6] ftp://nomads.ncdc.noaa.gov/NAM/analysis_only/

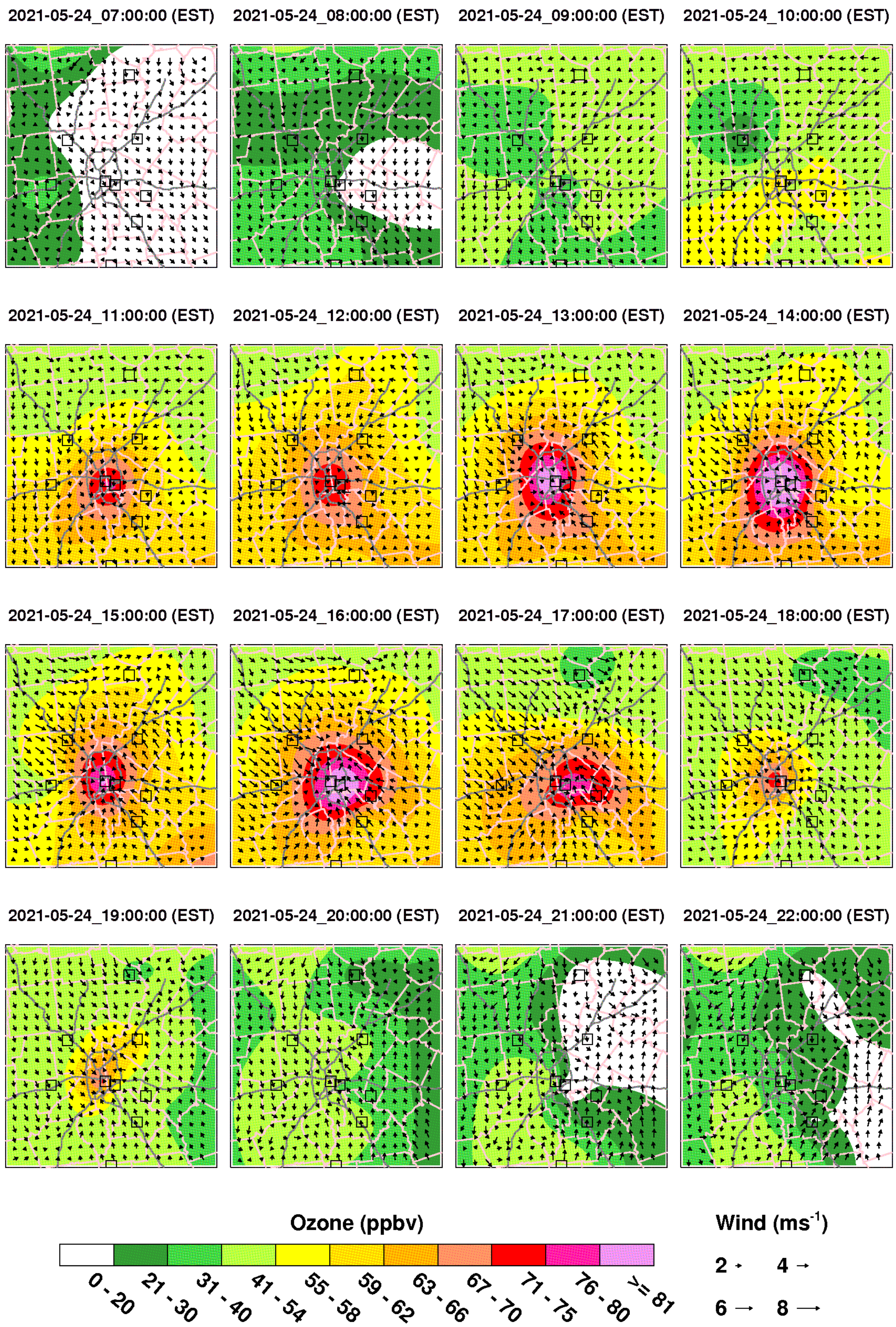

Figure 14. WRF simulated wind barbs and ozone observations (ppb) over the Metro Atlanta area from 7 AM to 10 PM on May 24, 2021. Ozone monitors are in black squares. The ozone exceedances occurred at the United Ave. and South DeKalb monitors.

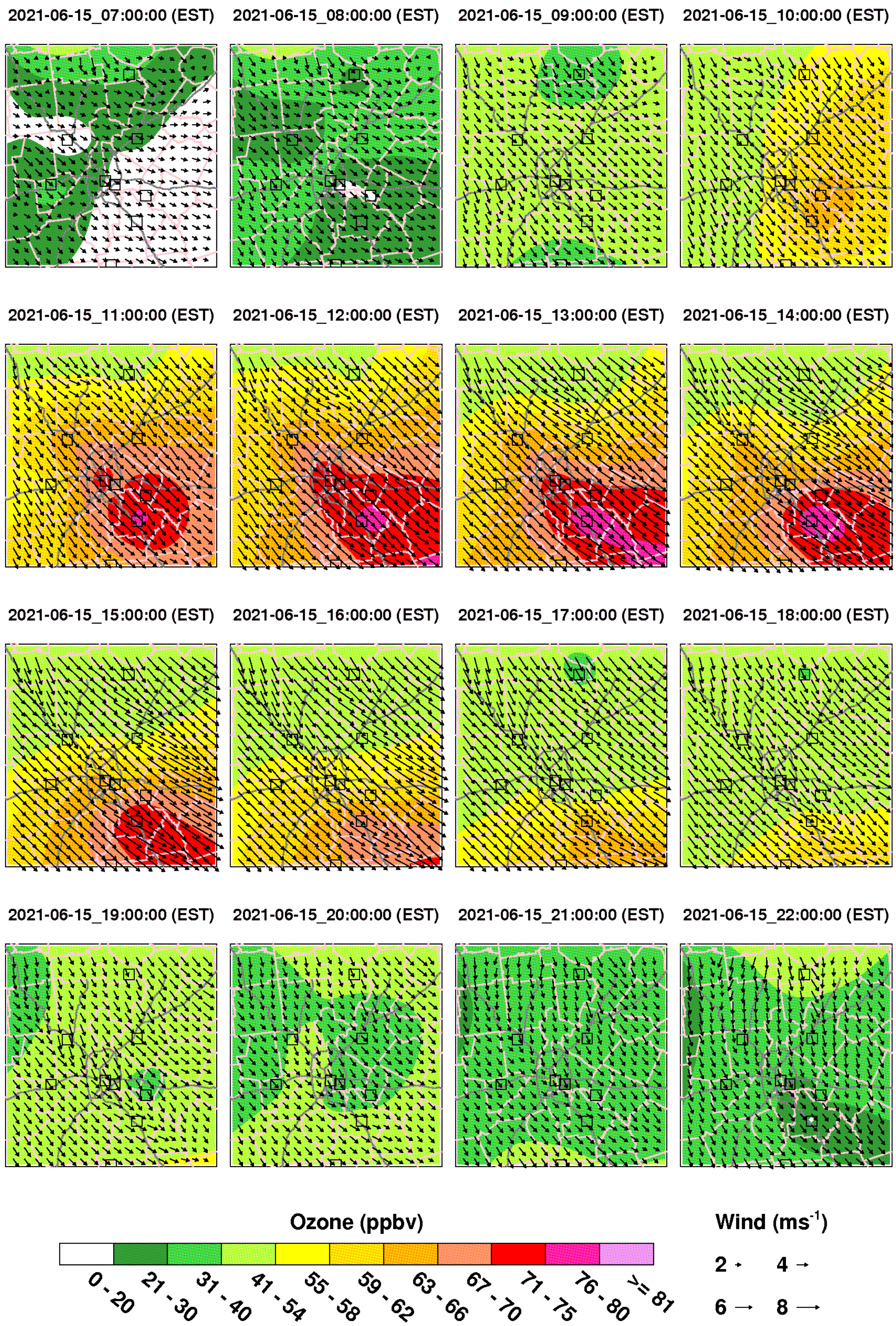

Figure 15. WRF simulated wind barbs and ozone observations (ppb) over the Metro Atlanta area from 7 AM to 10 PM on June 15, 2021. Ozone monitors are in black squares. The ozone exceedance occurred at the McDonough monitor.

3.3. Ozone and NO_X Precursors

Ozone is not emitted directly into the air but formed by the reaction of VOCs and NO_X in the presence of heat and sunlight. The relationship of ozone and NO_X is nonlinear since NO_X can also deplete ozone through NO_X titration (i.e., $O_3+NO \rightarrow O_2+NO_2$). NO_X can be emitted from passenger cars, trucks, and various non-road vehicles (e.g., construction equipment, boats, etc.) as well as stationary combustion sources such as power plants, industrial boilers, cement kilns, and turbines. In the Metro Atlanta area during 2017, 52.4% of NO_X emissions were from on-road mobile sources and 21.2% from non-road mobile sources (Figure 16).

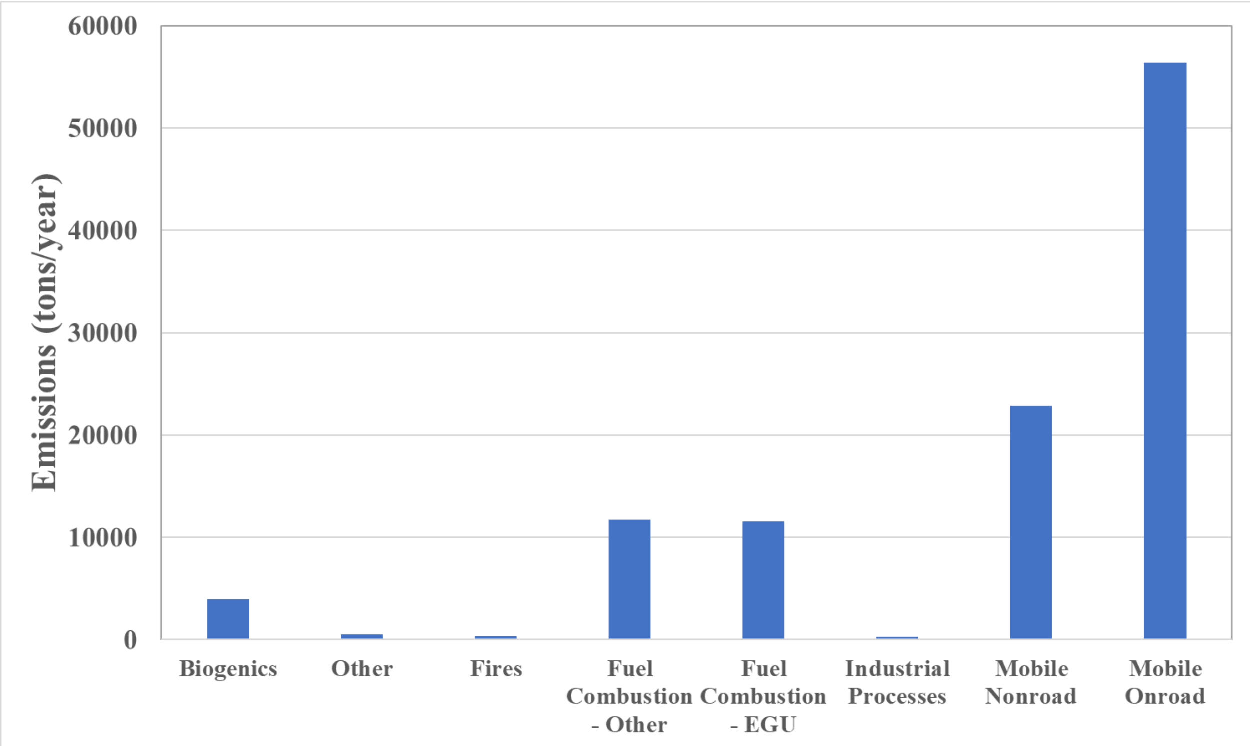

Figure 16. 2017 NO_X emissions (tons/year) by source sectors in the Metro Atlanta area.

In this report, the impacts of local NO_X on ozone exceedances are investigated by analyzing NO_X concentrations at the South DeKalb monitor and two roadside monitors (NR-285 and NR-GA Tech) located adjacent to major interstates (Figure 17) during ozone seasons (April – October). The two roadside monitors are investigated to identify impacts from on-road mobile NO_X emissions. Scatter plots of MDA8O3 and NO_X measurements at 8 AM and 4 PM (Figure 18) at the South DeKalb monitor imply that high ozone concentrations generally occur when NO_X concentrations are within a specific window. When NO_X concentrations are low in the morning, ozone concentrations in the afternoon are also low since there are not enough radicals available to produce ozone. However, when NO_X concentrations are too high (>100 ppb at 8:00 AM or >10 ppb at 4:00 PM), the excess NO_X removes ozone via NO_X titration. Figure 18 shows that high ozone concentrations in the Metro Atlanta area are highly correlated with low relative humidity (dry condition).

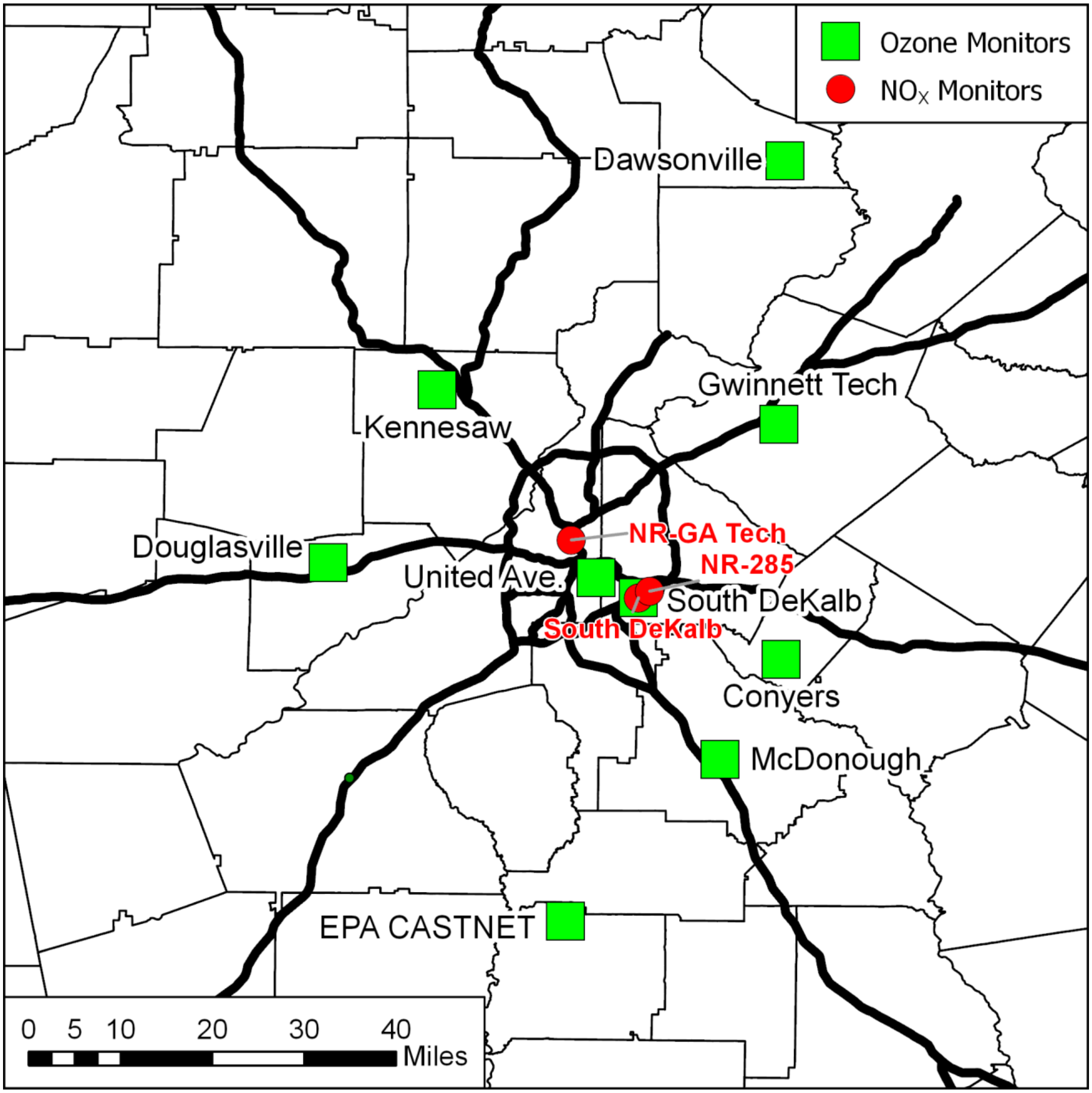

Figure 17. Locations of ozone and NO_X monitors in the Metro Atlanta area.

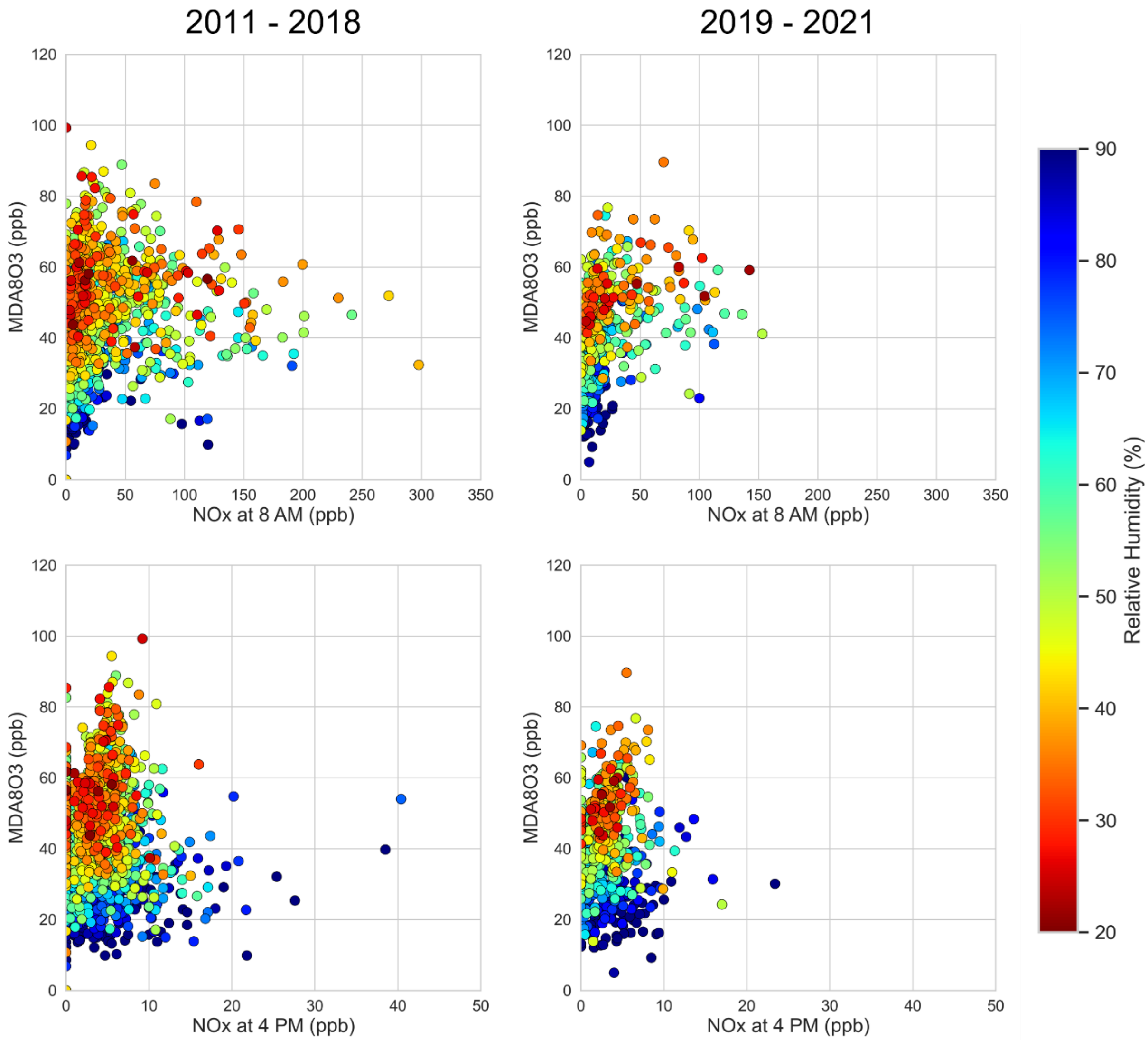

Figure 18. Scatter plots of MDA8O3 and NOx at 8 AM (top row) and 4 PM (bottom row) at the South DeKalb monitor. The color of dots reflects afternoon (noon-6 PM) relative humidity levels.

3.3.1. Diurnal Patterns of NO_X concentrations on Ozone Exceedance Days

Figure 19 contains three paired boxplots for NO_X concentrations by hour of day during the 2019-2021 ozone seasons at the three NO_X monitors[7]: all days ("Apr-Oct, 2019-2021") and ozone exceedance days at ozone monitors in the Metro Atlanta area ("On O3 Exceedance Days"). There is a clear diurnal variation in NO_X concentrations, peaking in the morning when NO_X emissions are high due to commuter traffic and NO_X emissions are trapped at low altitudes as the planetary boundary layer (PBL) is still quite low. Then, NO_X concentrations rapidly decrease as the PBL expands and photochemistry becomes more active during the day. Finally, NO_X concentrations increase again during nighttime as the PBL drops to a lower altitude trapping the NOx emissions closer to the surface.

NO_X concentrations at the two roadside monitors (NR-285 and NR-GA Tech) for all ozone season days are higher than those at the South DeKalb monitor for the same period. However, for ozone exceedance days, NO_X concentrations at the South DeKalb monitor are comparable with those at NR-285, especially from 6 AM to 8 AM, when traffic volumes are highest although the pattern is not clear for NO_X concentrations during evening/nighttime compared with morning time. In addition, NO_X concentrations at the South DeKalb monitor and NR-285 monitor are significantly higher on ozone exceedance days compared to all ozone season days. However, NO_X concentrations at NR-GA Tech were similar between all days and ozone exceedance days.

[7] No NO_X concentration data are available for NR-GA Tech sites in April 2019.

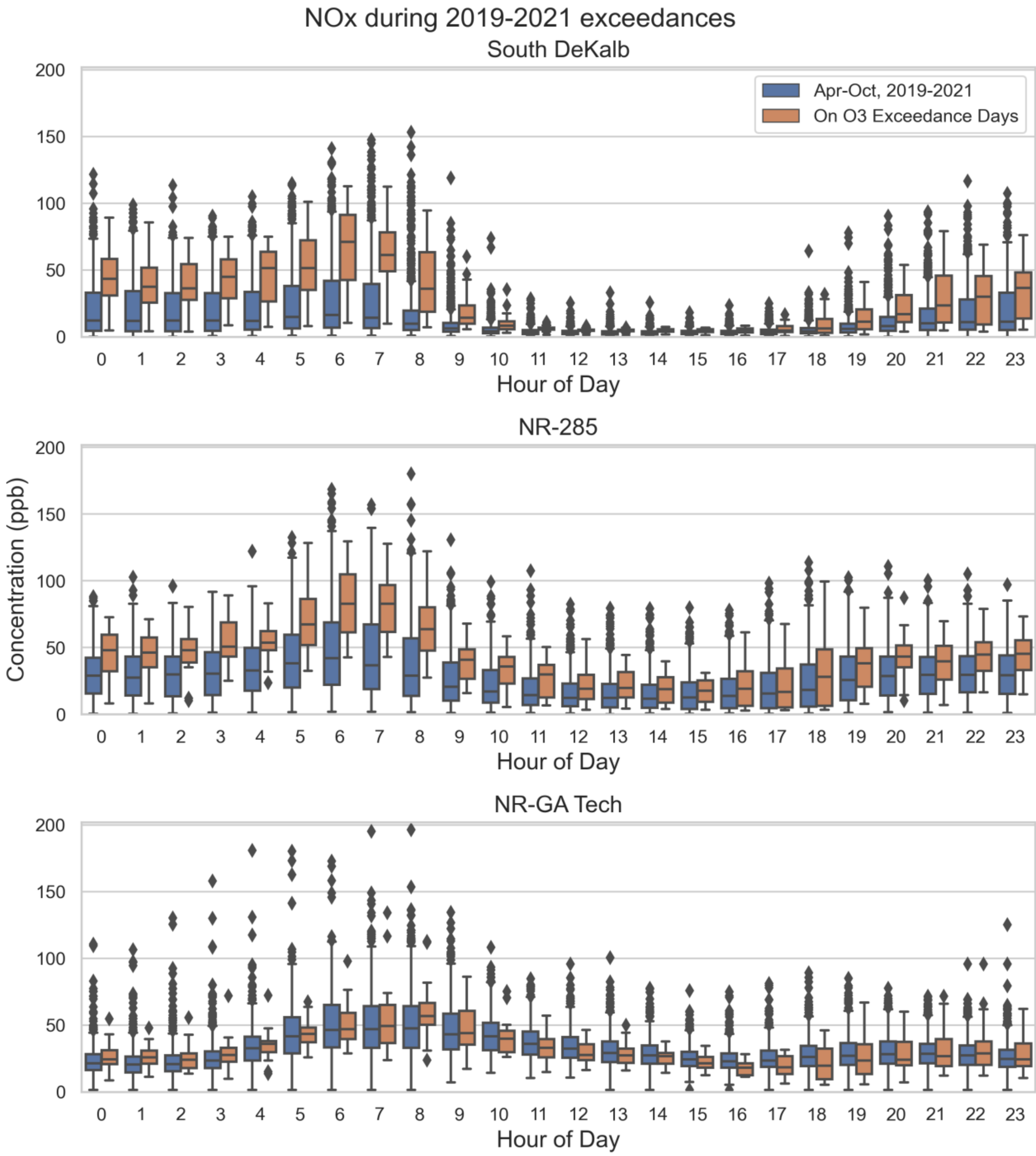

Figure 19. Boxplots by hour of day for NO_X concentrations during 2019-2021 ozone seasons at three NO_X monitors: all days ("Apr-Oct, 2019-2021") and ozone exceedance days ("On O3 Exceedance Days") at ozone monitors in the Metro Atlanta area.

3.3.2. Weekly and Monthly Patterns of NO_X concentrations on Ozone Exceedance Days

Variation of NO_X concentrations by day of week is analyzed by developing boxplots for NO_X concentrations during 5-7 AM at the three NO_X monitors (Figure 20). The averaged NO_X concentrations at 5-7 AM are chosen since they are likely correlated with high ozone levels as identified in the diurnal pattern analysis for the NO_X concentrations. The NO_X concentrations are higher on weekdays than the weekends, corresponding to similar traffic patterns (i.e., heavier commuter traffic during weekdays than weekend). Sunday morning NO_X concentrations are typically lower than Saturday morning. The boxplots are overlaid with NO_X concentrations on ozone exceedance days (red circles). In general, NO_X concentrations on ozone exceedance days are higher than average conditions.

Variation of NO_X concentrations by month is then analyzed by developing similar boxplots for averaged NO_X concentrations during 5-7 AM at the three NO_X monitors (Figure 21). The mean morning time NO_X concentrations at the two roadside monitors are between 25 and 50 ppb, while the mean morning time NO_X concentrations at the South DeKalb monitor tend to be less than 21 ppb throughout the ozone season. NO_X begins to increase through colder months such as October because there is less photochemistry to remove atmospheric NO_X. NO_X concentrations at the NR-285 and NR-GA Tech monitors also start to increase in September and October. The boxplots are overlaid with NO_X concentrations on ozone exceedance days (red circles). Exceedances took place in all ozone season months (i.e., April-October). The morning time NO_X concentrations on an ozone exceedance day are generally higher than the mean NO_X concentrations in that month at South DeKalb and NR-285. However, approximately half of the exceedance days at the NR-GA monitor show lower NO_X concentrations.

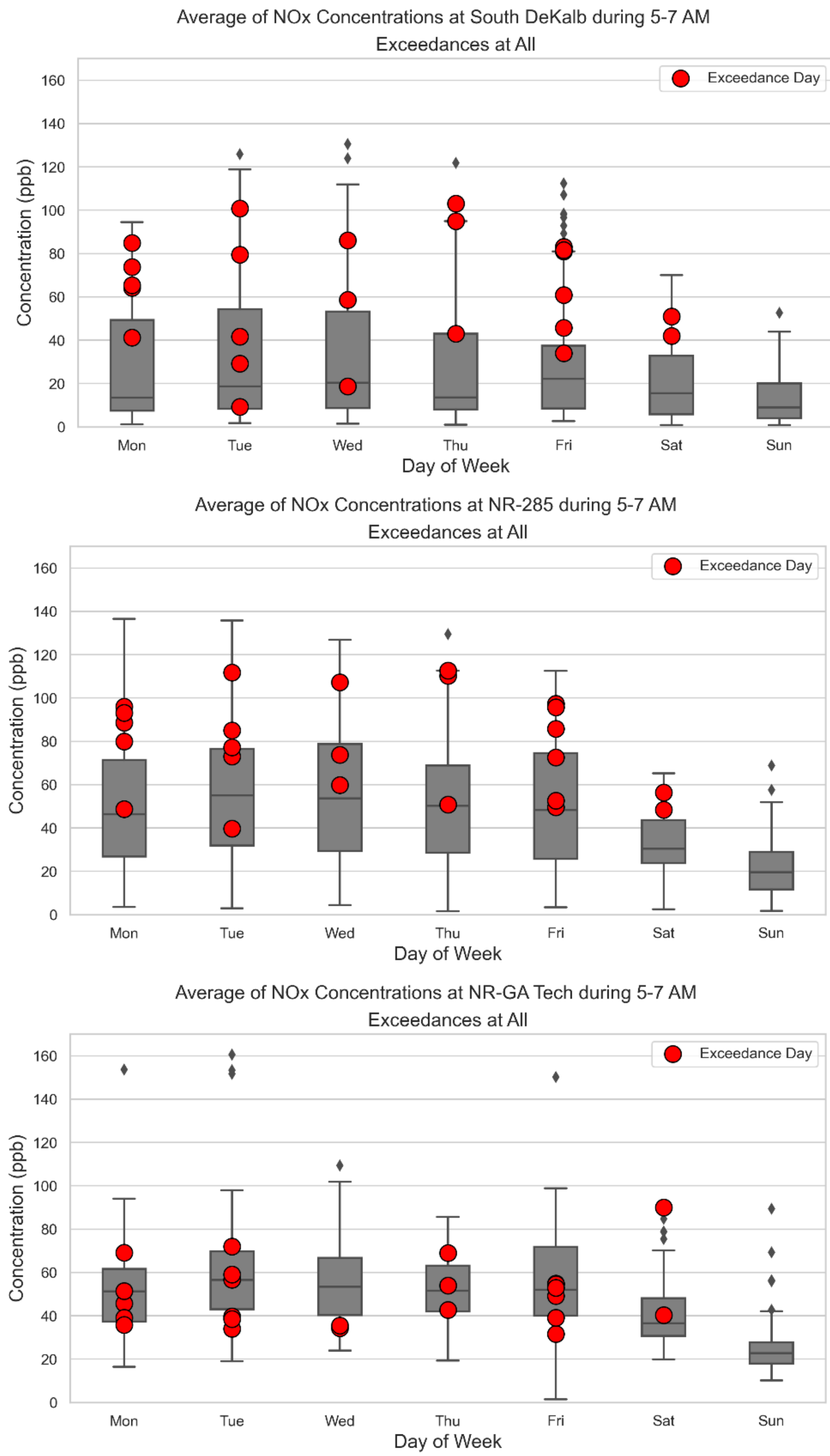

Figure 20. Boxplots by day of week for average NO_X concentrations during 5-7 AM during the 2019-2021 ozone seasons at three NO_X monitors. Red dots are NO_X concentrations on ozone exceedance days at each NO_X monitor. NO_X concentrations are not available for April 2019 at the NR-GA Tech monitor and on July 2, 2019 at the NR-285 monitor.

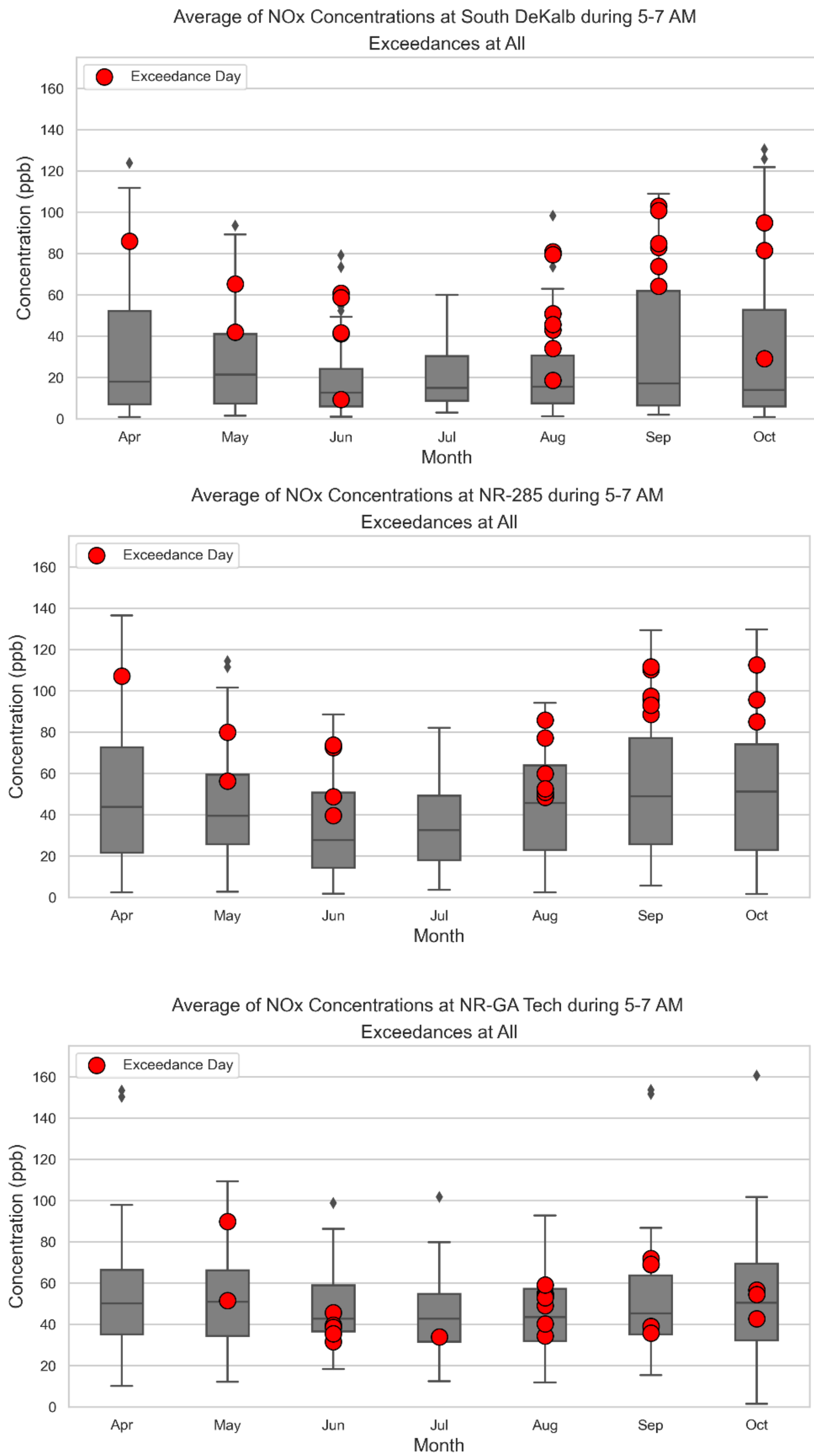

Figure 21. Boxplots by month for NO_X concentrations at 5-7 AM during the 2019-2021 ozone seasons at three NO_X monitors. Red dots are NO_X concentrations on ozone exceedance days at each monitor. NO_X concentrations are not available for April 2019 at the NR-GA Tech monitor and on July 2, 2019 at the NR-285 monitor.

3.3.3. Ozone and Traffic Conditions

Past studies indicated that NO_X and VOCs emission rates tend to be higher in congested traffic conditions (Anderson, et al., 1996; De Vlieger, et al., 2000; Zhang et al., 2011). In the Metro Atlanta area, NO_X emissions are mainly from mobile sources (Figure 16). Thus, the impact of traffic congestion in the Metro Atlanta area on ozone exceedances was further investigated by analyzing hourly Google traffic maps. Traffic conditions in Google traffic maps are displayed in four colors (green, orange, red, and dark red) as pixels (hereafter, "traffic pixels"). Each traffic pixel represents a different traffic condition: green for free flow, orange for light congestion, red for heavy congestion, and dark red for severe congestion. Since detailed historical traffic data were not publicly available, screenshots of Google traffic maps over the Metro Atlanta area were captured every 10 minutes from April 1 to October 31 during 2019-2021. Higher numbers of red and dark red traffic pixels indicate more serious congestions than those of green and orange. Figure 22 is an example screenshot for October 30, 2019 at 17:40 EST which showed the heaviest traffic (i.e., the highest number of red and dark red pixels) in 2019.

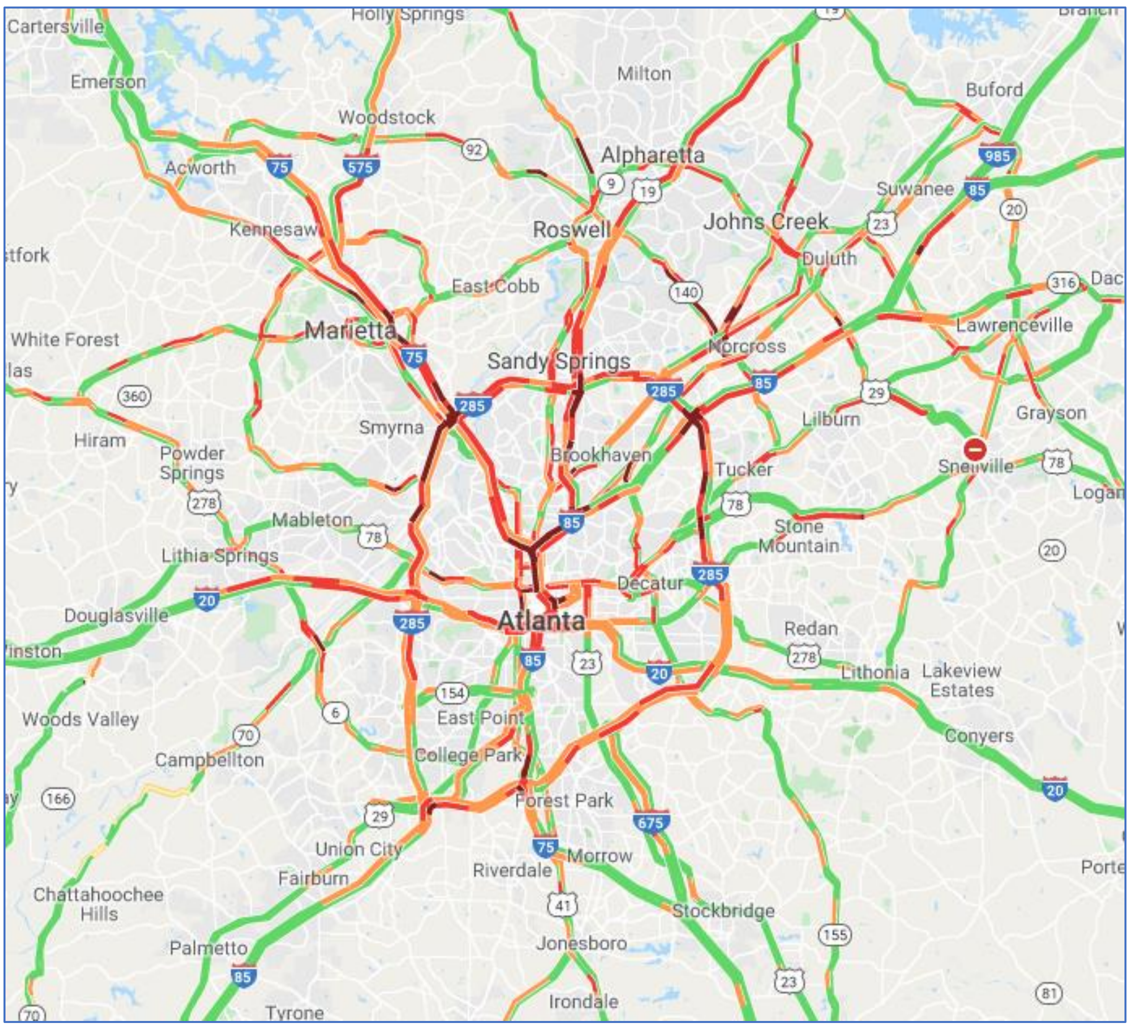

Figure 22. Google traffic map for the Metro Atlanta area for the hour with the heaviest traffic in 2019 (October 30 at 17:40 EST).

For each hour, the average number of traffic pixels for each color was calculated from screenshots that were captured every 10 minutes. A total of 91,711 screenshots were collected in the 2019-2021 ozone season. Traffic data analysis is presented in Eastern Standard Time (EST) to be consistent with other analyses. Statistics show that the numbers of hourly traffic pixels in Google traffic maps range from 381 to 50,147, with a mean of 45,820 (Table 6). There are 14 hours of missing data in 2019-2021.

Table 6. Statistics of the number of pixels by colors in the hourly google traffic map over the Metro Atlanta area.

Color	Max	Min	Median	Mean	Standard Deviation
Dark Red	1358	0	40	99	152
Red	5353	0	114	471	808
Orange	15161	0	1145	1831	1648
Green	49467	381	44629	43418	4703
Total	**50147**	**381**	**46685**	**45820**	**3572**

Traffic conditions varied greatly with the hour of the day (Figure 23). Most traffic pixels are in green while a lot of dark red, red, and orange pixels appeared in the Atlanta urban core. There are two peaks for the number of pixels in dark red, red, and orange: one peak during the morning rush hours of 6-8 AM EST (7-9 AM EDT) and the other in the evening rush hours of 3-6 PM EST (4-7 PM EDT). Overall, the 2019 traffic congestion is the highest and the 2020 traffic congestion is the lowest. The lower congestion in 2020 is related to the COVID pandemic. In 2021, the number of dark red, red, and orange pixels during the morning rush hours and the number of dark red pixels during the evening rush hours were similar to the 2019-2021 3-year average. Also, the number red and orange pixels in 2021 during the evening rush hours were similar to the number of 2019 pixels. Studies indicate that many employees may be permanently working from home or will continue to telework more frequently than they did prior to the pandemic.[8]

[8] https://gacommuteoptions.com/home/return-to-office/covid-19-commute-impact-report/

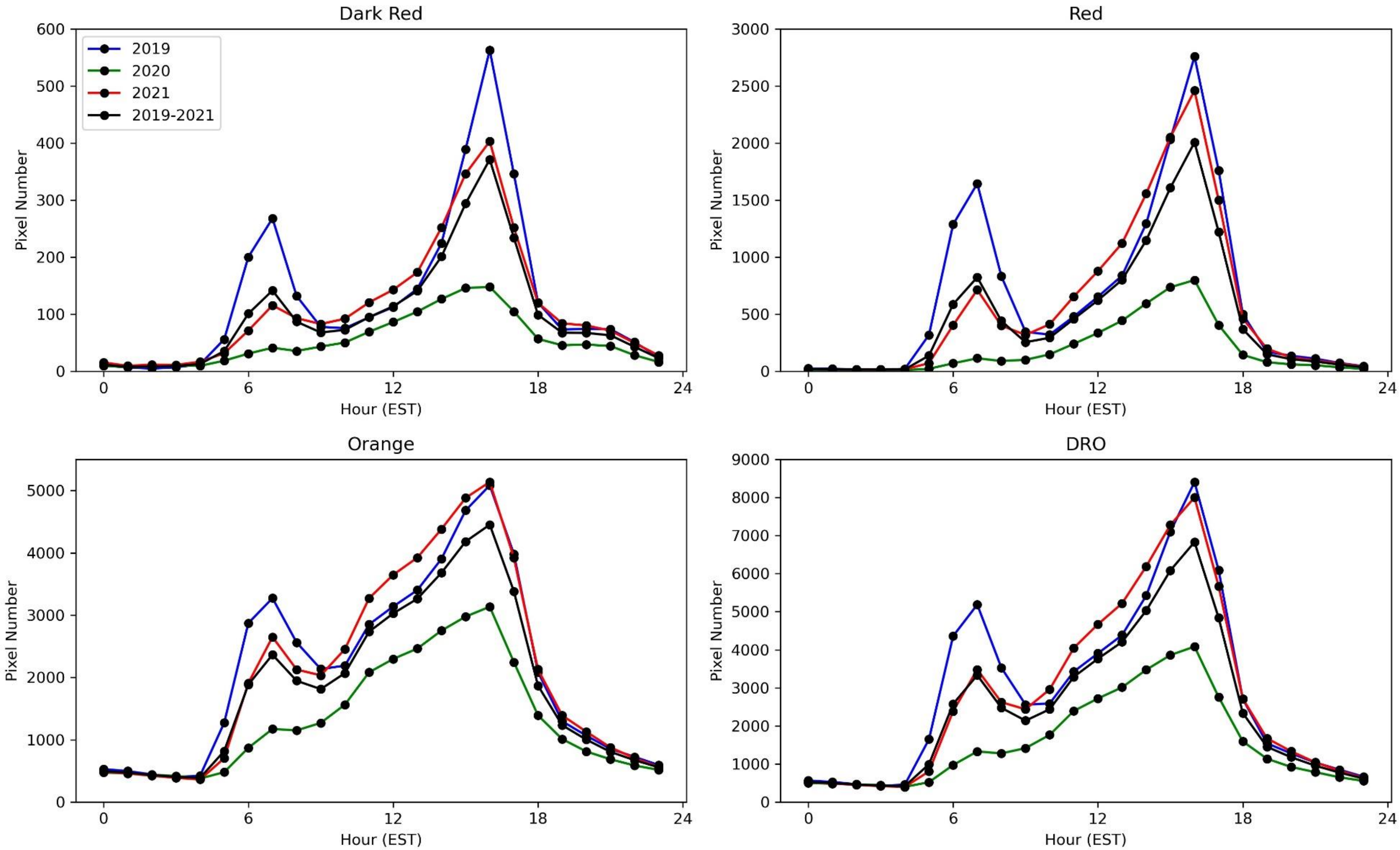

Figure 23. The average number of hourly traffic pixels over the Metro Atlanta area in 2019, 2020, 2021, and 2019-2021. DRO is the sum of dark red, red, and orange pixels.

In this report, the numbers of pixels for dark red, red, and orange were added together and referred to as DRO pixels to represent the overall congestion levels. A mean percentage of the total number of DRO pixels to the total number of all traffic pixels is 5.3%. During morning and evening rush hours, the percentage of the total number of DRO pixels to the total number of all traffic pixels can reach 7.2% and 15.5%, respectively (Figure 24).

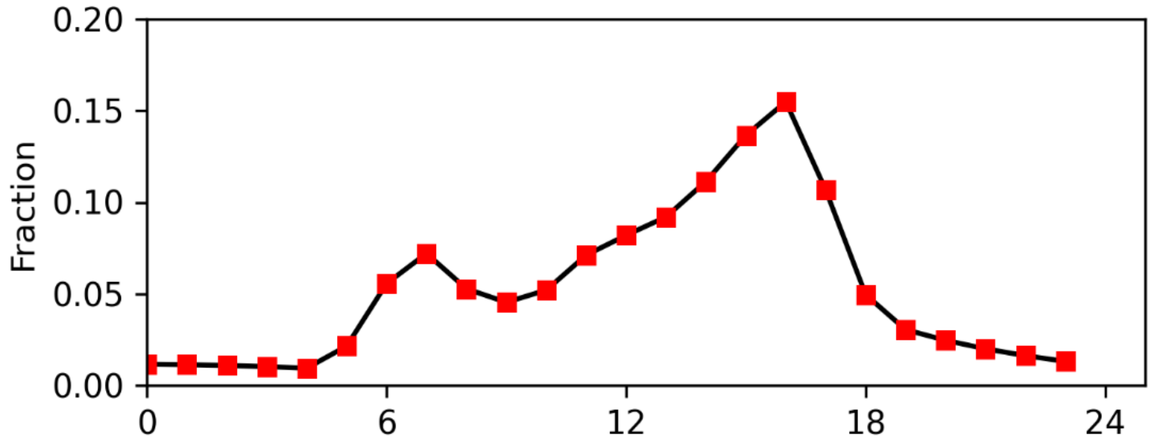

Figure 24. The average fractions of the number of DRO pixels to the total pixels in the hourly Google traffic pixel counts over the Metro Atlanta area in 2019-2021.

The hourly traffic conditions varied greatly with the day of week. The number of DRO pixels was much lower on weekends than weekdays. Peak traffic patterns were different; two peaks for the weekdays and one longer plateau for the weekend (Figure 25). During the weekdays, the number of DRO pixels increases gradually from Monday to Friday, except that the number of DRO pixels for the morning period on Friday is less than other weekdays. This pattern may be because people are leaving early for the weekend and more transient traffic comes through town going other places on Friday. For weekends, the number of DRO pixels on Saturday is higher than Sunday.

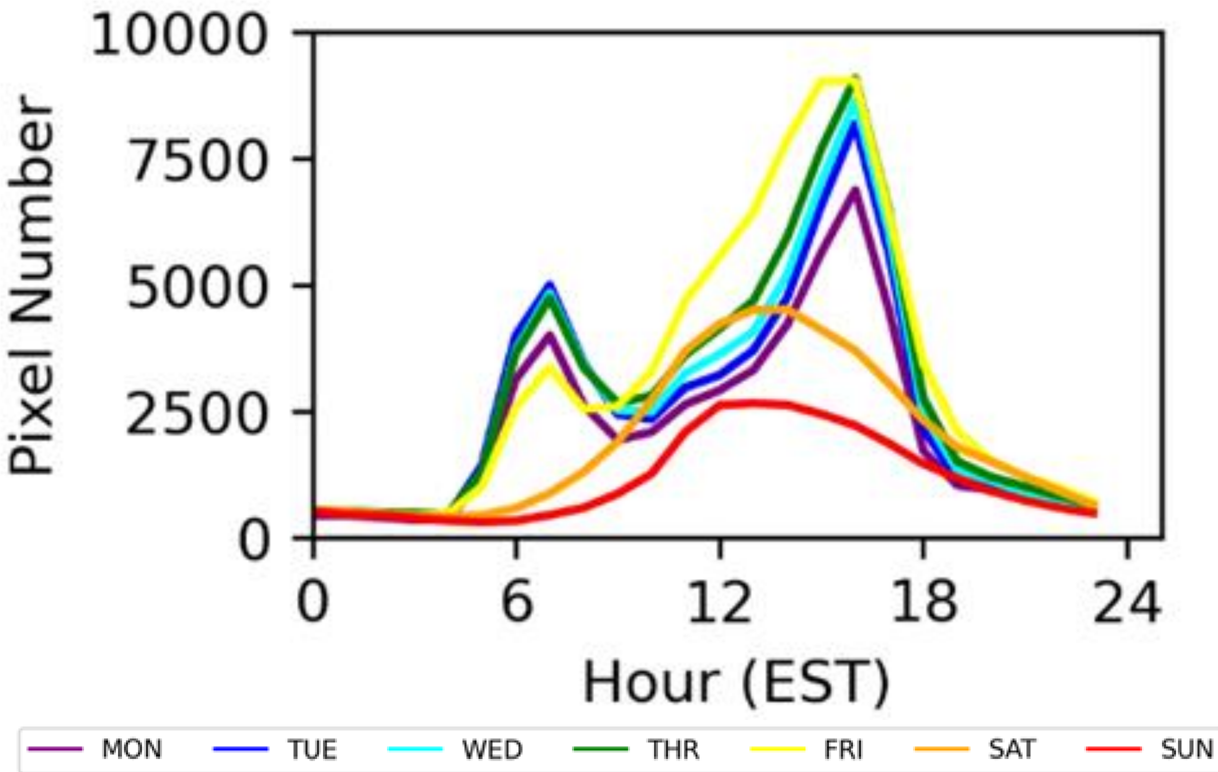

Figure 25. Numbers of DRO pixels on each day of week over the Metro Atlanta area in 2019-2021.

The hourly numbers of DRO pixels on all ozone exceedance days were compared with the hourly averages on all weekdays and weekends (Figure 26). In general, the numbers of DRO pixels are higher than the average during the morning traffic hours on weekdays. This finding suggests that managing NOx emissions during the morning traffic hours can be a key to addressing ozone exceedance days in the Metro Atlanta area.

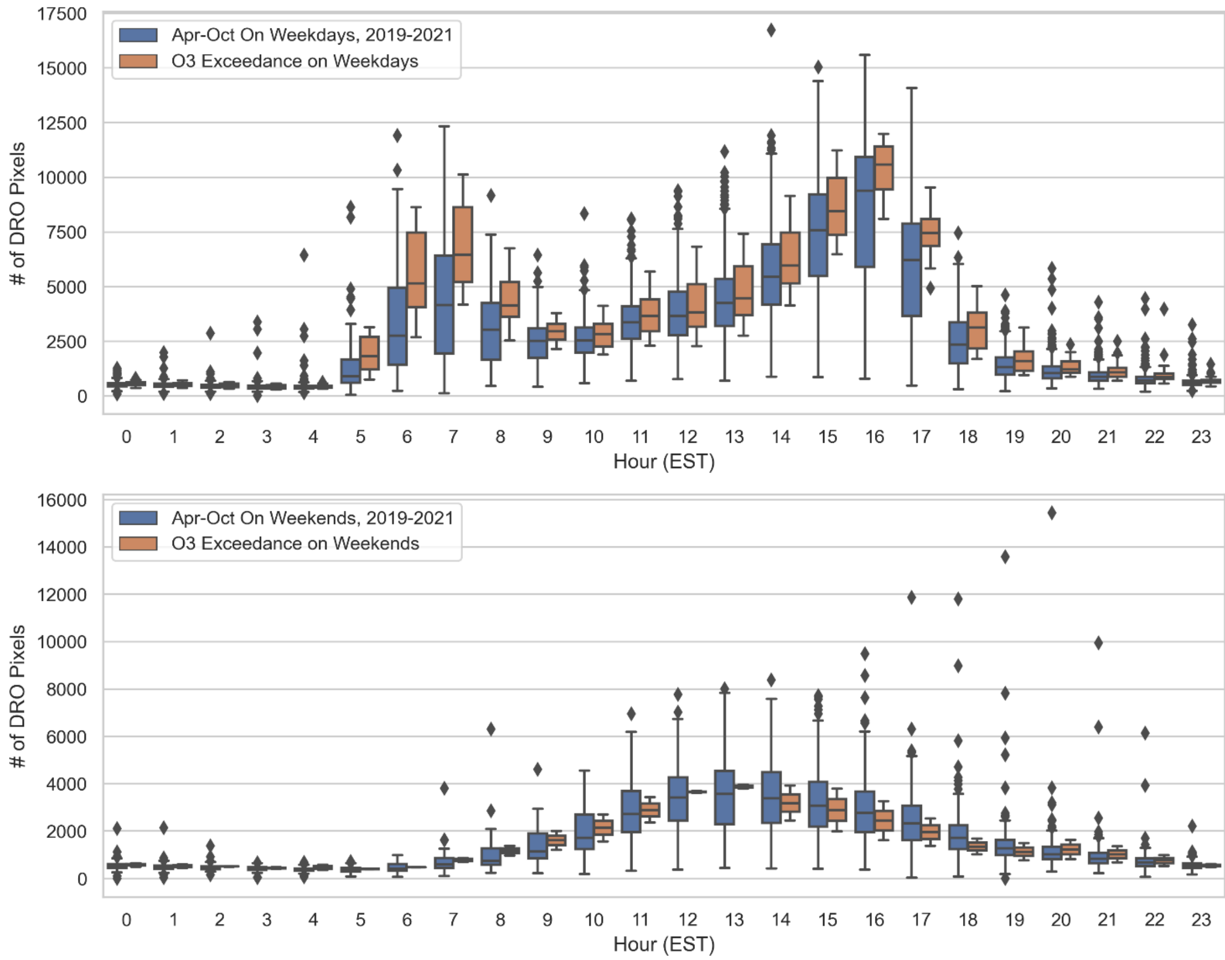

Figure 26. Comparison of numbers of hourly DRO pixels (i.e., a proxy of traffic jam) on all weekdays (top) and all weekend days (bottom) of ozone season days (blue) and ozone exceedance days (orange) during 2019-2021.

4. NOx Emissions during 2019-2021

4.1. TROPOMI Satellite NO_X Data

Spatial NO_X distributions in the Metro Atlanta area are evaluated using the latest remote-sensing NO_2 products by TROPOspheric Monitoring Instrument (TROPOMI) on board the European Copernicus Sentienl-5P satellite[9]. The TROPOMI tropospheric NO_2 columns became available after July 2018. TROPOMI provides NO_2 information around 1:30 PM when local ozone production is near its daily peak. The standard tropospheric TROPOMI NO_2 column product has a resolution of 7×3.5 km^2. TROPOMI has much higher spatial resolution than NASA Ozone Monitoring Instrument (OMI) NO_2 product and provides better daily representations of the surface NO_X conditions[10]. It can be used to identify NO_2 hot spots over the Metro Atlanta area.

EPD processed the 7×3.5 km^2 data onto a 1.3×1.3 km^2 WRF grid over Georgia. Daily TROPOMI NO_2 columns were downloaded from the RSIG server[11] by setting minimum quality flag of 50 and maximum cloud fraction of 0.3. The NO_2 column data were processed into the monthly maximum and monthly average NO_2 columns in June, July, August, and the 3-month period of June-August (JJA) during 2019, 2020, 2021, and 2019-2021 over the Metro Atlanta area (see Appendix B for details). The hot spots (i.e., red pixels) are indicative of high local NO_X emissions. Potential high NO_X emissions sources are the on-road mobile emissions from passenger vehicles and heavy-duty diesel vehicles that are traveling along I-85/I-75/I-285, aircraft emissions from HJAIA, and Plant Bowen. The monthly maximum NOx emissions and monthly mean NOx emissions were lower in 2020 compared to 2019 and 2021. The 3-month (JJA) maximum NOx emissions were highest in 2019 (Figure 27), while the 3-month (JJA) mean NOx emissions were highest in 2021 (Figure 28).

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[9] https://sentinels.copernicus.eu/web/sentinel/user-guides/sentinel-5p-tropomi

[10] TROPOMI NO2 data were used as a proxy for NO_X emissions in this report.

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

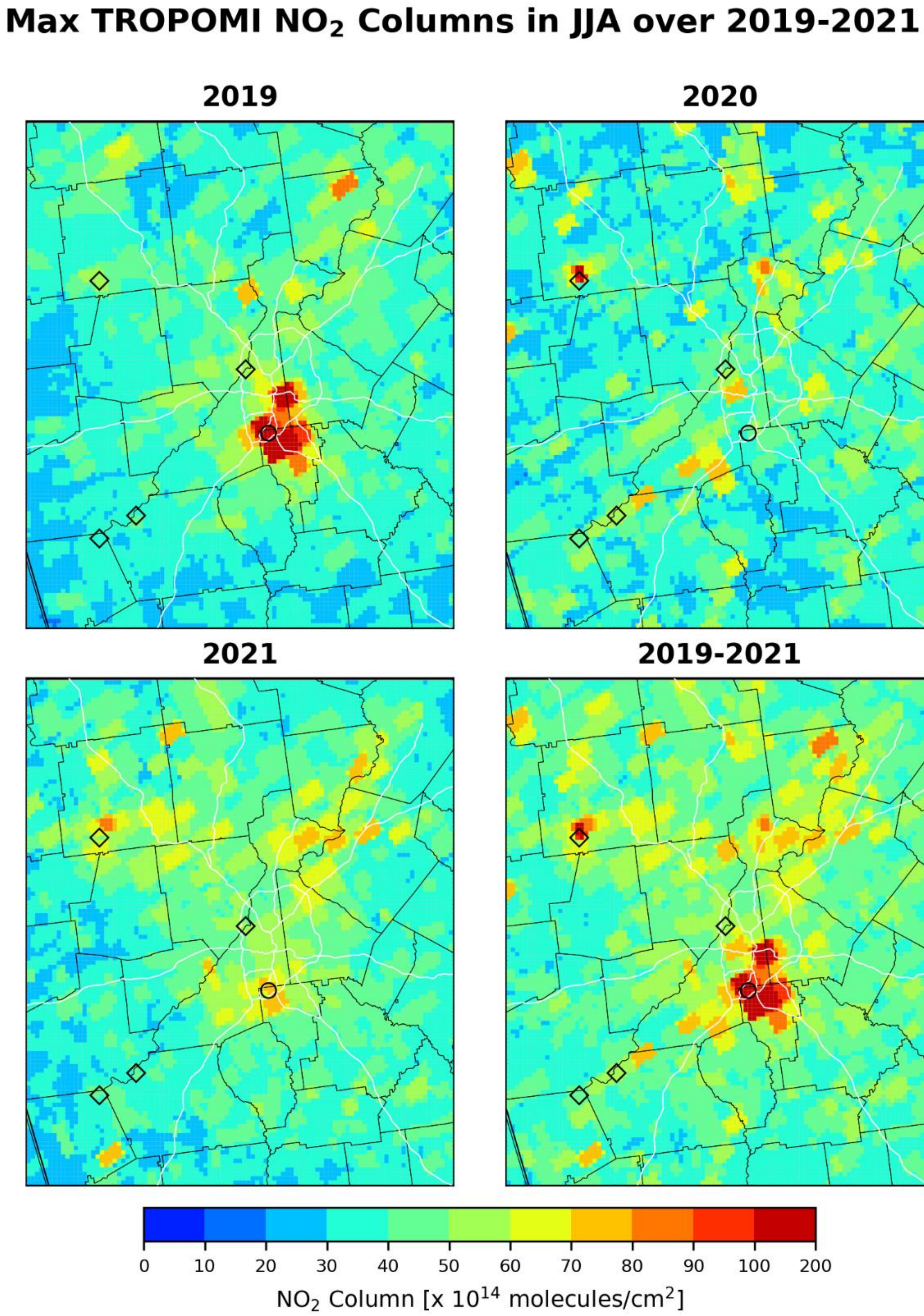

Figure 27. Maximum TROPOMI Tropospheric NO_2 columns over the Metro Atlanta area in June-August during 2019, 2020, 2021, and 2019-2021.

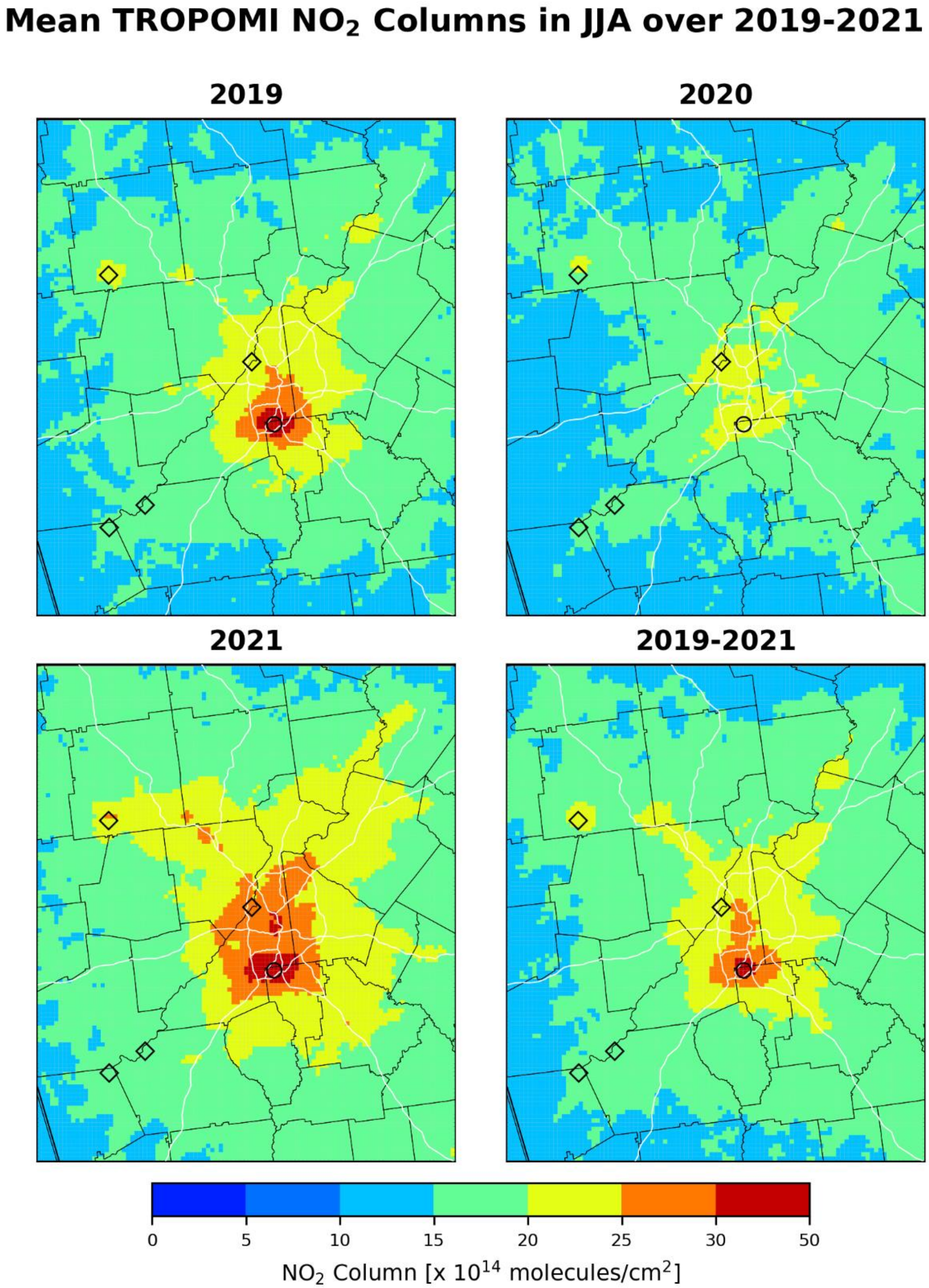

Figure 28. Mean TROPOMI Tropospheric NO_2 columns over the Metro Atlanta area in June-August during 2019, 2020, 2021, and 2019-2021.

A comparison of daily NO_2 columns for the 3-day period around June 14, 2019 (an exceedance day) shows significant increases in NO_2 concentrations on the ozone exceedance day (Figure 29). Additional 3-/4-day daily TROPOMI NO_2 plots are presented in Appendix B. The correlation of high ozone and NO_X indicate that NO_X played an important role in the ozone formation on the exceedance day.

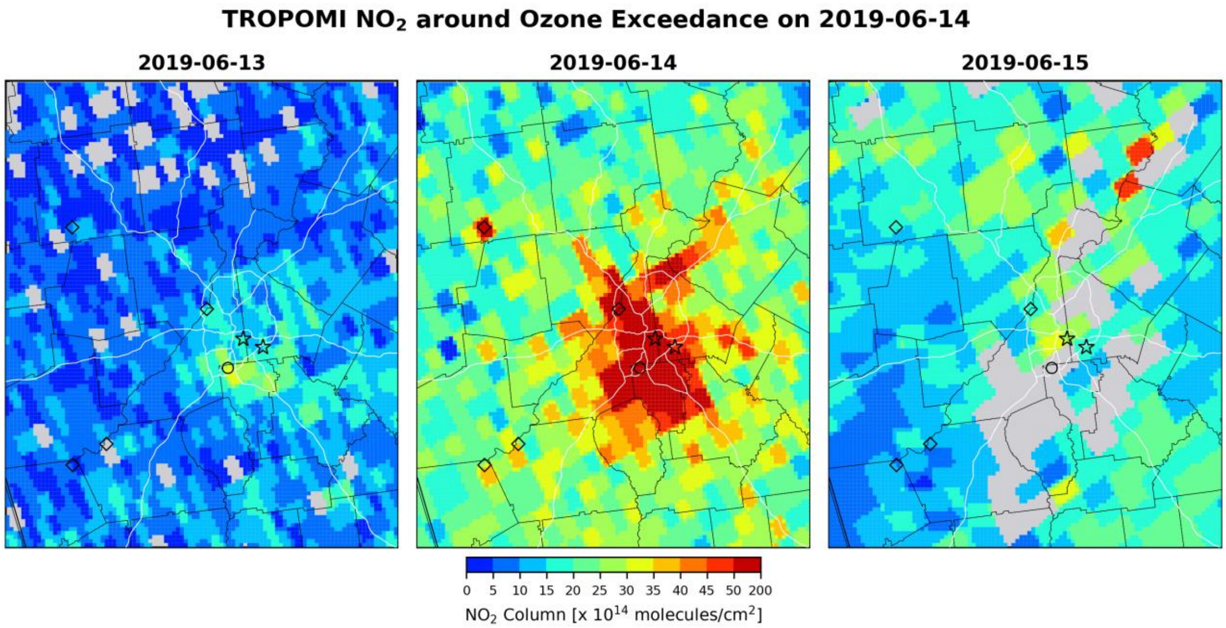

Figure 29. Daily TROPOMI NO_2 tropospheric columns over the Metro Atlanta area on June 13-15, 2019. Power plants, the Hartsfield-Jackson Atlanta International Airport, exceedance monitors are depicted as hollow diamonds, the circle, and stars.

4.2. NO_X Emissions from the Atlanta Airport and EGUs

As noted in final ozone reports in the past, HJAIA was perceived as a potential major contributor for ozone exceedances in Atlanta. Compared with 2019, aviation activities (as a proxy for aviation NO_X emissions) at HJAIA were reduced in 2020, especially for April-June, but returned to 80% of the 2019 level in 2021 (Figure 30). Airport emissions will likely not return to 2019 levels for several years as businesses are replacing in-person business trips with less costly virtual options.[12]

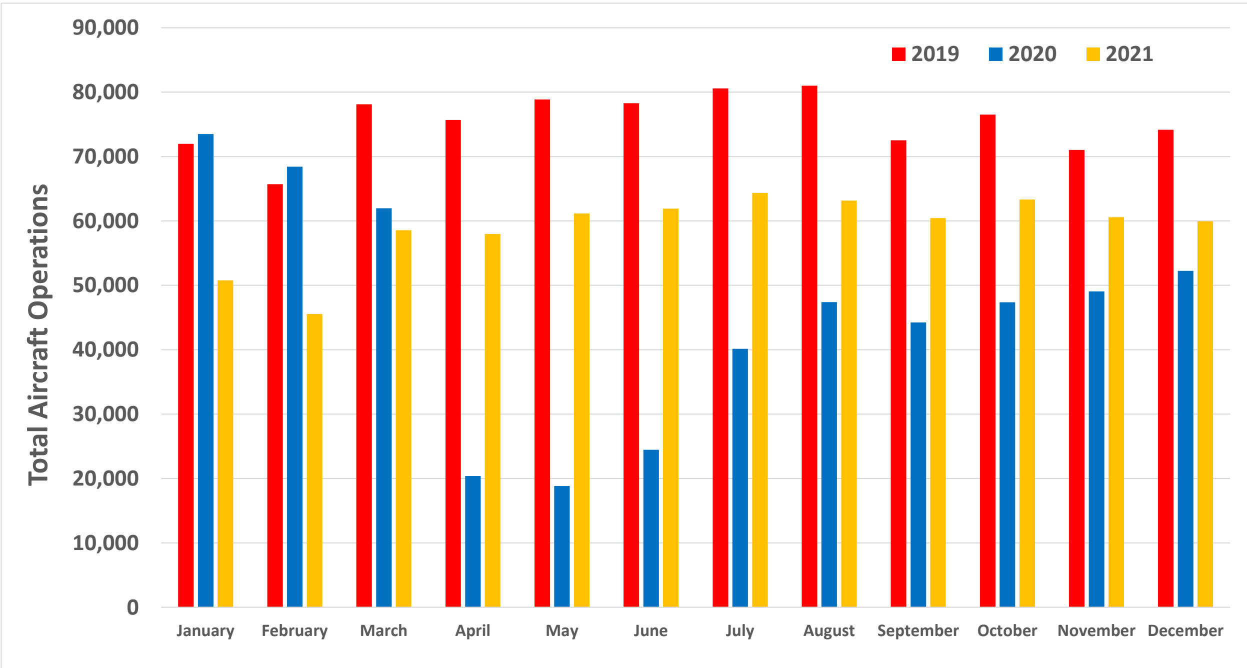

Figure 30. Monthly total aircraft operations at the Hartsfield-Jackson Atlanta International Airport in 2019, 2020, and 2021

In general, NO_X emissions from electricity generating units (EGUs) in Georgia during the ozone season were lower in 2020 and 2021 compared with 2019 (Figure 31). However, EGU NO_X emissions for July and August of 2020 and 2021 were similar to those during July and August of 2019. While some of the decreased NOx emissions in 2020 may be attributed to the COVID pandemic, much of the power plant emissions decrease in 2020 and 2021 was due to a significant increase in the use of renewable power generation.[13]

[12] https://aci.aero/news/2021/03/25/the-impact-of-covid-19-on-the-airport-business-and-the-path-to-recovery/

[13] https://ieefa.org/ieefa-u-s-georgia-solarhydro-electricity-output-tops-in-state-coal-generation-during-first-half-of-2020/

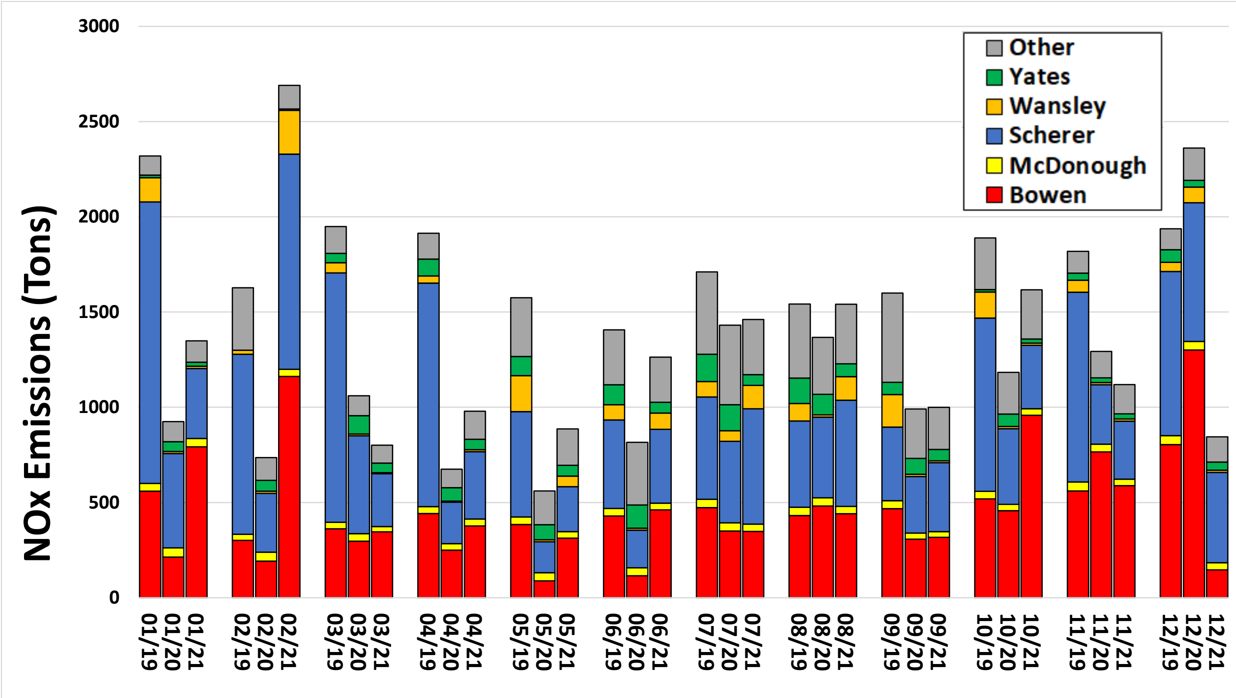

Figure 31. Monthly EGU NOx in Georgia for 2019-2021.

5. Ozone Regression Analysis

Multiple linear regression (MLR) analysis was previously used to quantify the relationship between Atlanta MDA8O3 and environmental variables in a study (Cardelino, 2011). In this 2011 study, 15 environmental variables (O3-day1, weekday, and Julian day in addition to 12 meteorological variables) were used. O3-day1 is used to represent ozone on the previous day that may linger and contribute to ozone exceedances on the current day. Weekday is used to represent emissions variation due to human activities. Julian day is used to represent the variations of solar radiation throughout the ozone season. During the development of 2016 final ozone exceedance report, two additional environmental variables (relh1 and relh2) were added in the MLR analysis. As part of the 2017 report development, Julian day was replaced by the daily maximum solar elevation angle (SunAngle) to better represent the intensity of solar radiation because Julian day shows very poor correlation with ozone in the 2016 MLR analysis.

For this report, the MLR model used daily data of MDA8O3 and 17 environmental factors (Table 7) to build a linear relationship of Atlanta MDA8O3 and environmental factors assuming independency among these environmental factors:

$$y = \alpha_0 + \sum_{i=1}^{i=17} \alpha_i x_i$$

where, y stands for MDA8O3, x_i stands for the environmental factor, α_0 is an adjustment factor, and α_i is a weighting factor.

The correlation coefficients of MDA8O3 and the 17 environmental variables during ozone season were calculated for 2011-2018 and 2019-2021in Atlanta (Table 8 and Figure 32). The difference of correlation coefficients among these two periods illustrates how the relationships between Atlanta MDA8O3 and environmental variables changed through the years. The ranking of correlation coefficients is similar for 2011-2018 and 2019-2021. The top 6 most correlated environment variables (i.e., variables with the top 6 highest absolute value of ‘r’) are: ozone level one day ago, AM and PM relative humidity, AM and PM cloud coverage, and daily max temperature. Before 2019, the most correlated environmental variable is the daily maximum 8-hour average ozone one day ago (O_3-Day1). However, in 2019-2021, PM relative humidity are the most correlated environmental variables, followed by the daily maximum 8-hour average ozone one day ago (O_3-Day1), AM relative humidity (Relh1), AM and PM cloud coverage (Sky1 and Sky2), and daily maximum temperature (T_{max}). The newly introduced variable as part of the 2017 report development, the daily maximum solar elevation angel (SunAngle) is insignificant (r = 0.207) in 2019-2021. In general, the ozone exceedance days were associated with the following meteorological conditions:

1. Low relative humidity (dry)
2. High daily temperature (hot)
3. Low cloud coverage (high solar radiation)
4. High ozone on previous days (persistence)
5. Relatively low wind speed (calm)

Table 7. Daily variables used for the MLR analysis

Name	Definition	Formula	Unit
Tmax	Daily maximum temperature	max(tmpf)	degree of Fahrenheit
Tmin	Daily minimum temperature	min(tmpf)	degree of Fahrenheit
TDmax	Daily maximum dew point temperature	max(dwpf)	degree of Fahrenheit
TDmin	Daily minimum dew point temperature	min(dwpf)	degree of Fahrenheit
Pres1	Mean surface pressure in the morning (6-12 pm)	mean($mlsp_{(6\text{-}12)}$)	millibar
Pres2	Mean surface pressure in the afternoon (12-6 pm)	mean($mlsp_{(12\text{-}18)}$)	millibar
WDir1	Mean wind direction in the morning (6-12 pm)	mean($drct_{(6\text{-}12)}$)	degree from north
WDir2	Mean wind direction in the afternoon (12-6 pm)	mean($drct_{(12\text{-}18)}$)	degree from north
WSpd1	Mean wind speed in the morning (6-12 pm)	mean($sknt_{(6\text{-}12)}$)	m/s
WSpd2	Mean wind speed in the afternoon (12-6 pm)	mean($sknt_{(12\text{-}18)}$)	m/s
Sky1	Mean cloud coverage in the morning (6-12 pm)	mean(max(skyc1,skyc2,skyc3,skyc4) $_{(6\text{-}12)}$)	%
Sky2	Mean cloud coverage in the afternoon (12-6 pm)	mean(max(skyc1,skyc2,skyc3,skyc4) $_{(12\text{-}18)}$)	%
O3-Day1	Daily Maximum 8-hr average ozone one day ago	-	ppbv
WkDay	Day of week	Weekday(date)	n/a
SunAngle	Daily maximum solar elevation angle	See equations (1) and (2) below	degree
Relh1*	Mean relative humidity in the morning (6-12 pm)	mean($relh_{(6\text{-}12)}$)	%
Relh2*	Mean relative humidity in the afternoon (12-6 pm)	mean($relh_{(12\text{-}18)}$)	%

(1) Solar declination, $\delta = 23.45^o sin\left[\frac{Julian\ Day+284}{365} \times 360^o\right]$

(2) Daily maximum solar elevation angle, $\propto = asin(\cos(latitude)\cos\delta + \sin(latitude)\, sin\delta)$

Table 8. Correlation coefficients of MDA8O3 and environmental variables during ozone season by time periods during 2011-2019 in the Metro Atlanta area.

Name	2011-2018	2019-2021
Relh2	-0.63191	**-0.71597**
O3-Day1	**0.652111**	0.680288
Relh1	-0.60429	-0.67709
Sky1	-0.50766	-0.66621
Sky2	-0.40259	-0.57531
Tmax	0.461082	0.39577
WSpd1	-0.26994	-0.29874
WSpd2	-0.21695	-0.23742
Pres1	0.073952	0.21481
SunAngle	0.280538	0.206691
Pres2	0.047621	0.19025
Tdmax	-0.06449	-0.17843
Tdmin	-0.08285	-0.17712
WDir2	0.063949	0.059304
WkDay	-0.03268	-0.05126
Tmin	0.144671	0.045422
WDir1	0.037985	0.021079

Note: Top 6 absolute values are highlighted in red. The highest absolute value is in bold.

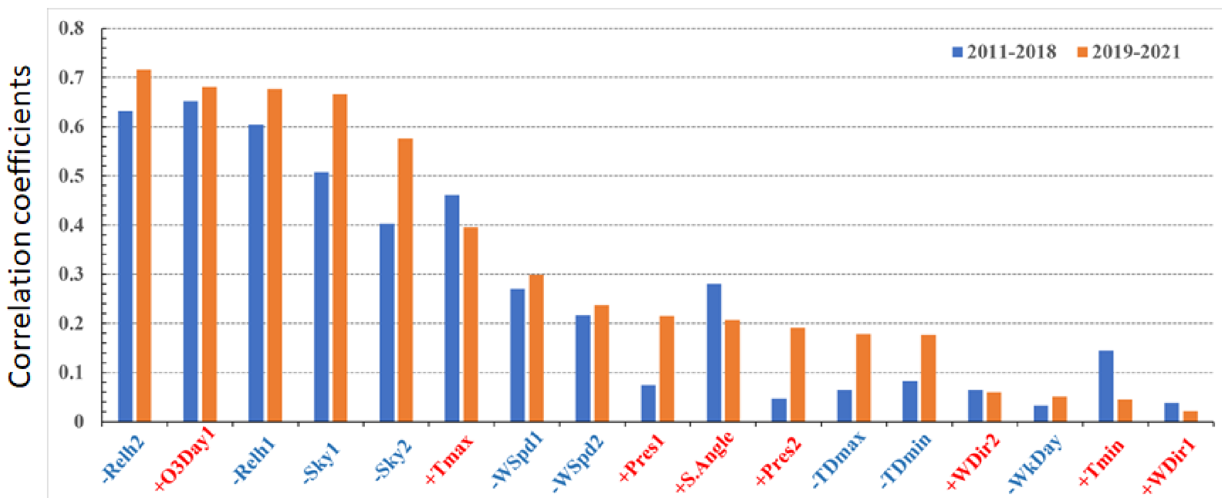

Figure 32. Correlation coefficients of MDA8O3 and environmental variables during ozone season by time periods during 2011-2018 (blue bars) and 2019-2021 (orange bars) in the Metro Atlanta area. Variables with positive correlation with MDA8O3 are labeled in red, and variables with negative correlation are labeled in blue.

The above meteorological conditions favor the chemical production of ozone in the lower troposphere. Low relative humidity may reduce the ozone loss through the reaction with water vapor (Seinfeld and Pandis, 1998). Ozone formation increases with high temperatures and low cloud coverage due to higher solar radiation, leading to more active ozone production. High ozone on previous days indicates that the ozone buildup was a multiple-day process. Calm conditions correspond to poor dispersion and less regional transport, indicating that the local ozone production is important for ozone exceedances in Atlanta.

The MLR ozone model was developed using 2011-2021 observation data, and then used 10-fold cross validation (CV) to evaluate O3 forecasting performance. Specially, the entire observation data collected during 2011-2021 was randomly split into 10 folds where each fold contains about 10% of data set. In each round of CV, nine folds of the data were selected to build the MLR model and the held-out subset was used for the model evaluation. This process is repeated 10 times until each fold has been treated as a validation data set. The performance was summarized in Table 9 by a set of evaluation metrics which include coefficient of determination (R^2), mean bias (MB), normalized mean bias (NMB), mean absolute error (MAE), normalized mean error (NME), root mean square error (RMSE), true positive rate (TPR), true negative rate (TNR), and critical success index (CSI). Overall, the updated MLR ozone model can explain about 72% of the ozone variance (or R^2). The mean bias (MB) and normalized mean bias (NMB) are identical in magnitude when comparing 2011-2021 vs. 2016-2021, but the 2011-2021 bias in negative and the 2016-2021 bias is positive. The TPR and CSI are best with the 2011-2021 data. Other statistical indexes, such as NMB and NME, are similar among the various MLR ozone models. The MLR model based on the 2011-2021 data is recommended due to higher TPR and CSI values relative to the other models, indicating the model has a higher opportunity to capture O3 exceedances. The coefficients of the MLR ozone model with 2011-2021 datasets are listed in Table 10.

Table 9. Performance of updated MLR ozone model using various datasets during 2011-2021.

Data range	R (1.00)	R^2 (1.00)	MB (0.00)	MAE (0.00)	NMB (0.00)	NME (0.00)	RMSE (0.00)	TPR (1.00)	TNR (1.00)	CSI (1.00)
2011-2021	0.853	0.728	-0.004	5.855	**-8e-05**	0.115	7.486	**0.394**	0.988	**0.350**
2012-2021	0.846	0.715	-0.013	5.804	-2e-04	0.116	7.418	0.292	0.992	0.264
2013-2021	0.844	0.712	**-0.001**	5.701	-3e-05	0.116	7.285	0.237	0.994	0.217
2014-2021	0.848	0.720	-0.015	5.678	-3e-04	0.115	7.224	0.255	0.994	0.235
2015-2021	0.854	0.729	-0.006	5.698	-1e-04	0.116	7.205	0.222	0.994	0.202
2016-2021	**0.857**	**0.734**	0.004	**5.594**	**8e-05**	**0.114**	**7.070**	0.213	**0.995**	0.198

MB is Mean Bias, **MAE** is Mean Absolute Error, **NMB** is Normalized Mean Bias, **NME** is Normalized Mean Error, **RMSE** is Root Mean Square Error, **TPR** is True Positive Rate, **TNR** is True Negative Rate, and **CSI** is Critical Success Index. Number below each metric are the values for a perfectly performing model. The best performance for each metric is indicated with red bold font.

Table 10. The coefficients of the MLR ozone model using dataset during 2011-2021.

Variable	Coefficient	Variable	Coefficient	Variable	Coefficient
O3-Day1	0.39485	Tdmin	-0.05323	WSpd1	-0.13172
Sky1	-2.46557	SunAngle	0.17396	WSpd2	-0.72349
Sky2	2.78841	Pres1	-0.79383	Relh1	-0.04407
Tmax	0.29471	Pres2	0.45927	Relh2	-0.44010
Tmin	-0.20038	WDir1	-0.01005	WkDay	-0.61875
Tdmax	0.13772	WDir2	0.00421	Constant	379.01952

6. Summary

Various analyses have been conducted to understand the causes of ozone exceedances in the Metro Atlanta area during 2019-2021. These analyses include: (1) an overview of ozone air quality in the Metro Atlanta area, (2) a trend of ozone concentrations and meteorological conditions during 2011-2021; (3) ozone exceedances for 2019-2021; (4) NO_X emissions for 2019-2021; and (5) the relationship between ozone and environmental variables. The analysis with animations of ozone and wind conditions were supplemented with ozone-wind analysis for ozone exceedance days. NO_X emission analysis was supplemented with TROPOMI NO_2 plots.

The maximum MDA8O3 values and the number of exceedance days during the 2011-2021 ozone seasons generally decrease over time. Currently, the Metro Atlanta area has no monitors with design values above 70 ppb. No monitors had a 4th highest concentration above 70 ppb in 2020 and 2021 while five monitors had their 4th highest concentrations above 70 ppb in 2019. With a few exceptions, meteorological conditions in 2019-2021 are similar to the 2011-2021 average conditions. During 2019-2021, AM and PM cloud coverages were less than the 2011-2021 average cloud. Daily maximum temperature in 2019 was higher than the 2011-2021 average while daily maximum temperature in 2020 and 2021 were lower. Morning and afternoon relative humidity values in 2019 were lower than 2011-2021 averages while 2020 and 2021 were higher.

During 2019-2021, the Metro Atlanta area experienced at least one ozone exceedance each year. The total number of exceedance days was 25 days. A total of 10 days out of 25 exceedance days showed exceedances at more than one monitor on the same day. Most exceedances occurred in the months of June, August, and September during 2019-2021. At the same time, more exceedances occurred in April and October (based on a percent basis) while less exceedances occurred in July compared with 2011-2018. During 2019-2021, relatively more ozone exceedances occurred on Monday, Tuesday, and Friday than 2011-2018. On all exceedance days in 2019-2021, meteorological conditions feature lower relative humidity, less cloud coverage, lower wind speeds, and higher daily max temperatures compared to non-exceedance days. The spatial pattern of ozone exceedance shows two distinctive association with winds. For ozone exceedances inside the Atlanta urban core, wind speeds were generally low (i.e., stagnant). For ozone exceedances that occurred outside of the Atlanta urban core, the general pattern is that wind blew from the urban core to the exceedance monitor.

Analysis of NO_X measurements in the Atlanta urban core area along with ozone measurements found that ozone exceedance occurred more often on weekdays than weekends when the NO_X emissions from the dominant NO_X source (on-road mobile) in the Metro Atlanta area are higher. The morning time NO_X measurements on ozone exceedance days also tend to be higher due to commuter traffic. In addition, NO_2 column hot spots such as I-75/I-85/I-285 and the Hartsfield-Jackson Atlanta International Airport were observed on ozone exceedance days with satellite data.

The MLR analysis has shown that ozone exceedances are likely to occur when relative humidity is low, cloud coverage is low, and daily maximum air temperature is high. In addition, relative humidity in the afternoon is the most significant factor in 2019-2021 while daily maximum 8-hour average ozone one day ago (O_3-Day1) used to show the strongest association. This indicates that ozone production on exceedance days in 2019-2021 has become more important than multi-day episodes that allow ozone to build-up over time.

In summary, the following factors likely contributed to ozone exceedances in the Metro Atlanta area during 2019-2021:

1) High daily maximum air temperature on exceedance days;
2) Low relative humidity, cloud coverage, and wind speeds;
3) Local ozone formation at monitors inside the urban core due to local precursor emissions from the Atlanta urban core;
4) Local transport of ozone and precursors from the Atlanta urban core to monitors outside the urban core; and
5) NO_X emissions from Hartsfield-Jackson Atlanta International Airport and local on-road mobile sources (likely due to high traffic congestion, especially in the morning hours).

The following studies and measurements are recommended to further understand the causes of future ozone exceedances in the Metro Atlanta area:

- Co-located measurements of NO_X and VOC species at United Ave.;
- Measurements of NO_X near the airport (e.g., EPD Tradeport parking lot or roof);
- Aircraft measurements (ozone, NO_X, VOCs, and CO) on elevated ozone days;
- Personal air sensors to understand ozone, NOx, and VOC spatial gradients;
- Ozone and NO_2 balloon soundings to understand vertical profiles;
- Ceilometer measurements to understand dynamics of atmospheric mixing;
- Ozone profiles from LIDAR;
- Geostationary satellite data from TEMPO (Tropospheric Emissions: Monitoring of Pollution) to be launched in December 2022;
- Additional traffic studies using vehicle count and speed data (Google maps and/or TOMTOM) or GDOT "Navigator" speed and traffic data; and/or
- High resolution photochemical modeling (e.g., 4- or 1-km grid cells) to examine the impact of various emission control strategies on ozone concentrations.

This additional information may help us explore new options to prevent future ozone exceedances in the Atlanta area.

7. References

Cardelino, C., M. Chang, J. St. John, et al. (2011). Ozone Predictions in Atlanta, Georgia: Analysis of the 1999 Ozone Season, J. Air & Waste Manage. Assoc. 51:1227-1236.

Seinfeld, J. H., S. N. Pandis (1998). Atmospheric chemistry and physics: from air pollution to climate change, Wiley.

Appendix A

Animation of ozone and wind conditions for ozone exceedance days in 2019-2021

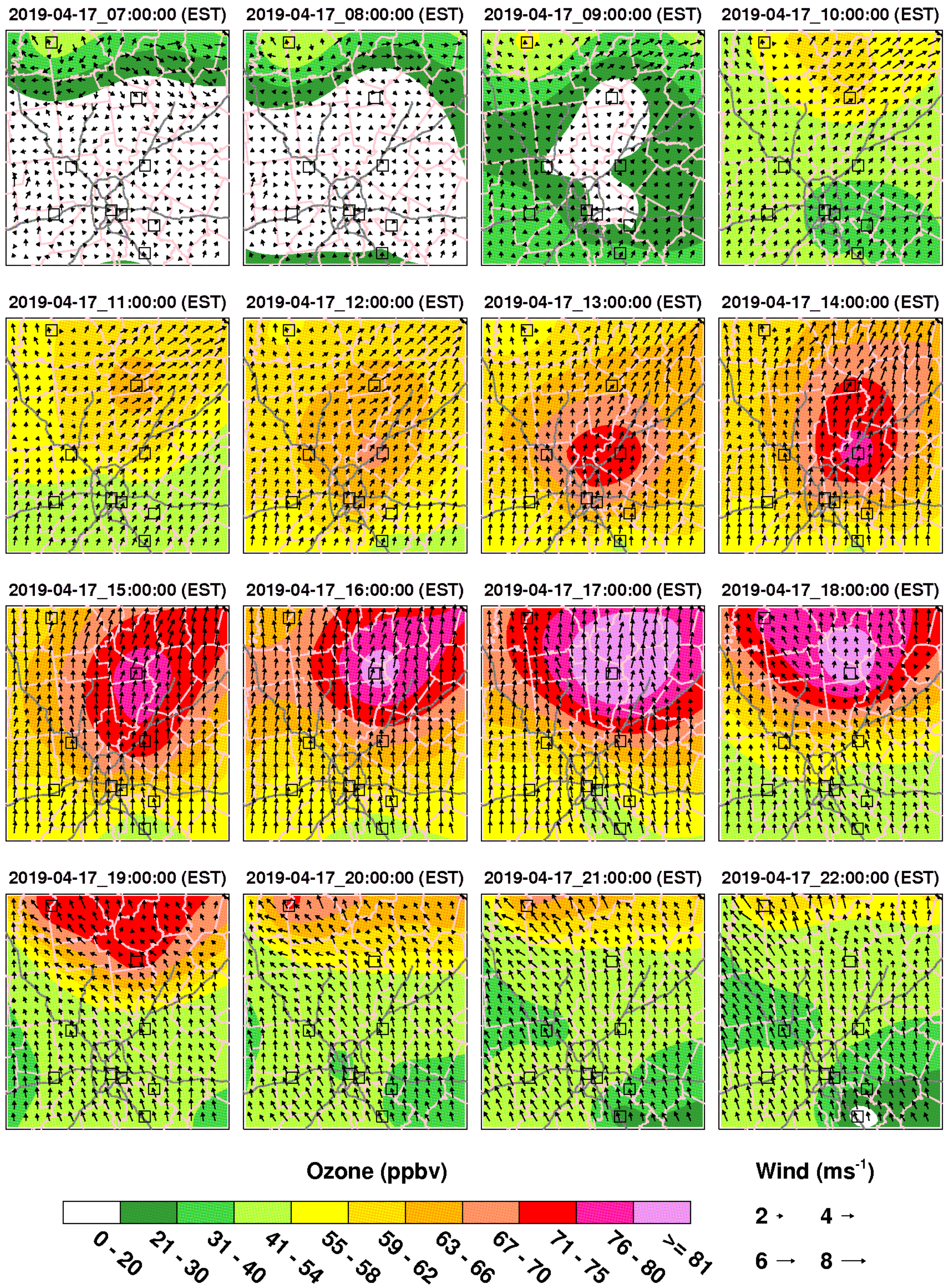

Figure A1. WRF simulated wind barbs and ozone observations (ppb) over the Metro Atlanta area from 7 AM to 10 PM on April 17, 2019. Ozone monitors are in black squares. The ozone exceedance occurred at the Dawsonville monitor.

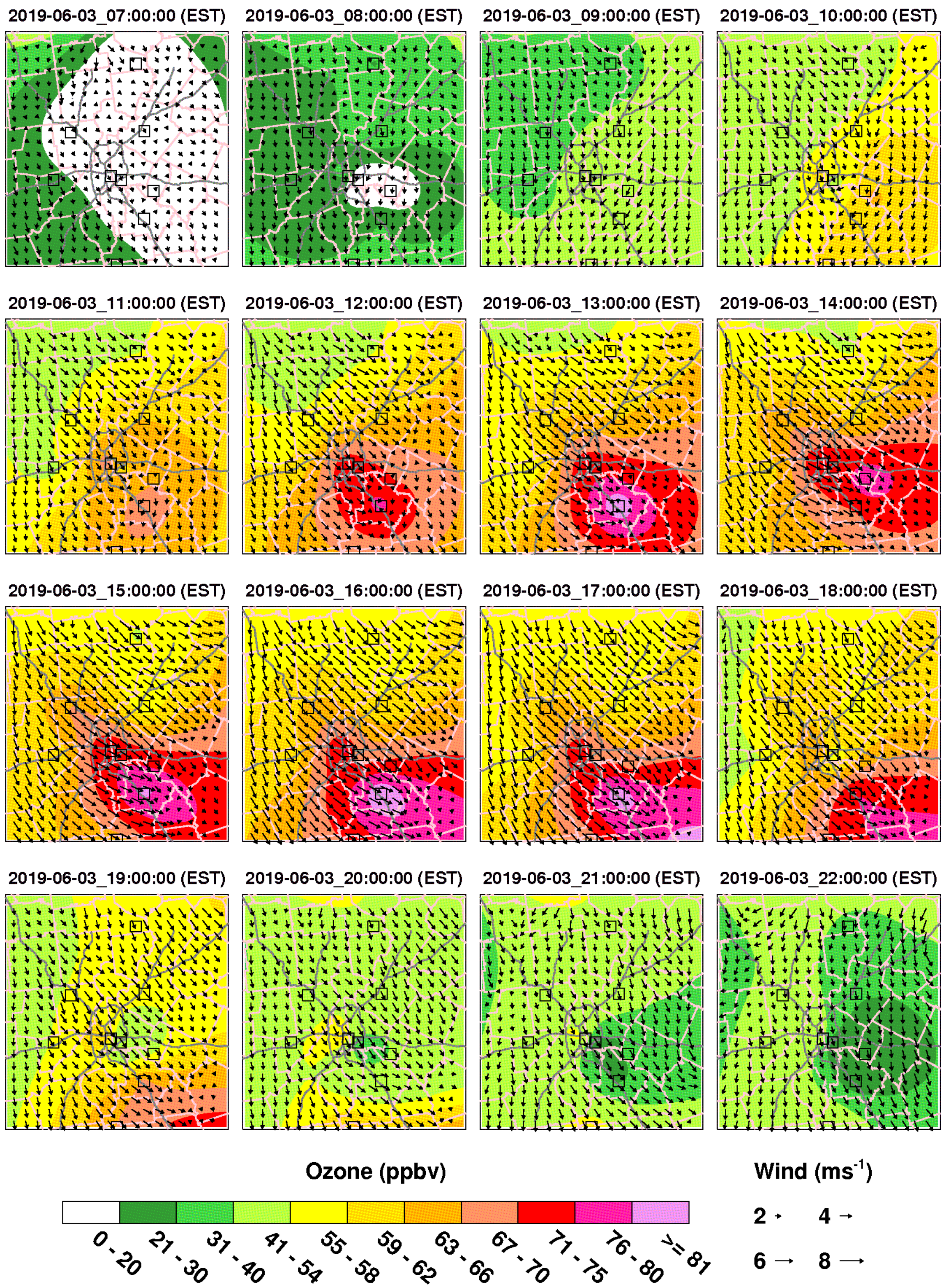

Figure A2. WRF simulated wind barbs and ozone observations (ppb) over the Metro Atlanta area from 7 AM to 10 PM on June 3, 2019. Ozone monitors are in black squares. The ozone exceedance occurred at McDonough, Macon-Forestry, United Ave., and Conyers monitors.

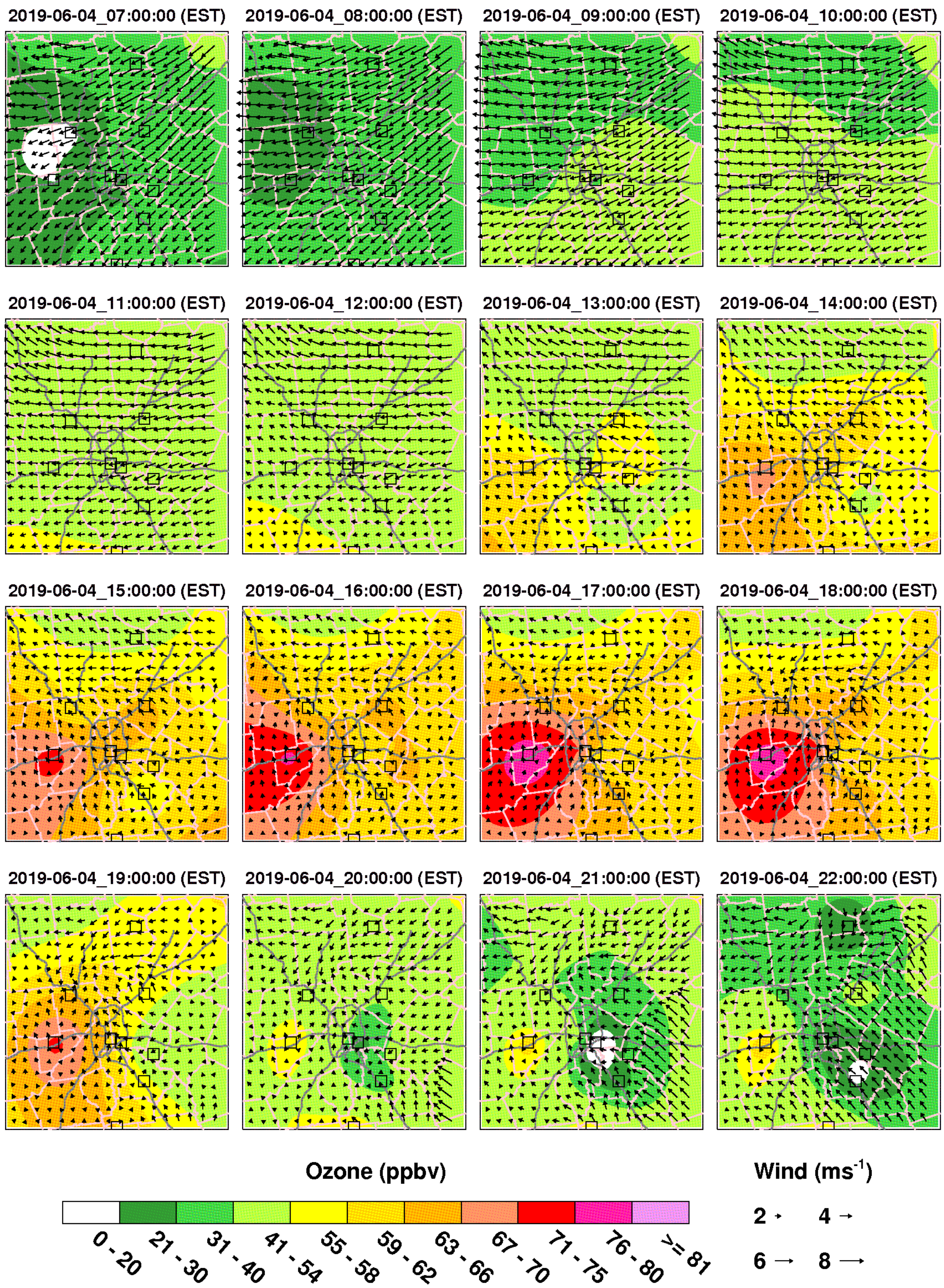

Figure A3. WRF simulated wind barbs and ozone observations (ppb) over the Metro Atlanta area from 7 AM to 10 PM on June 4, 2019. Ozone monitors are in black squares. The ozone exceedance occurred at the Douglasville monitor.

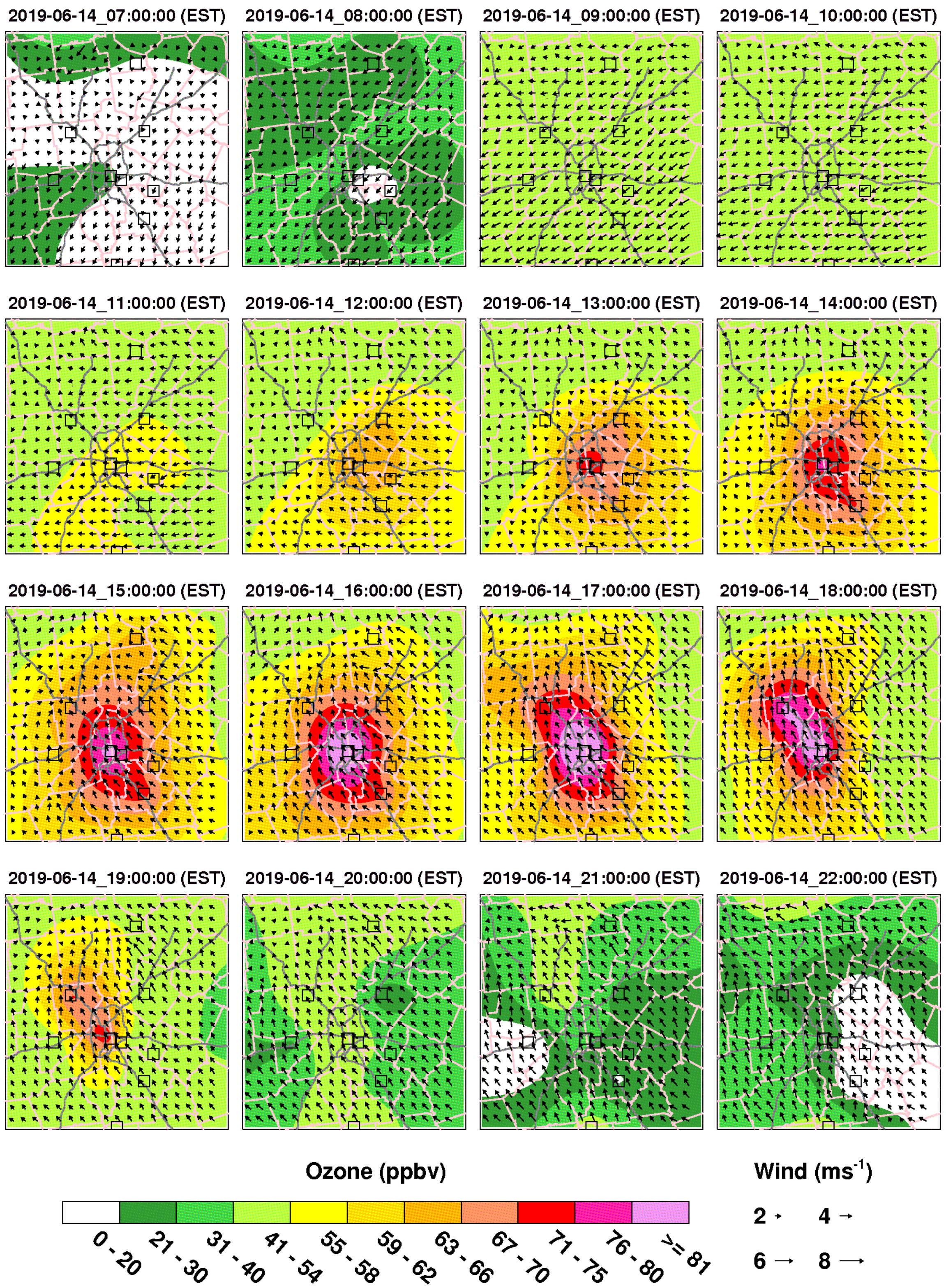

Figure A4. WRF simulated wind barbs and ozone observations (ppb) over the Metro Atlanta area from 7 AM to 10 PM on June 14, 2019. Ozone monitors are in black squares. The ozone exceedance occurred at United Ave. and South DeKalb monitors.

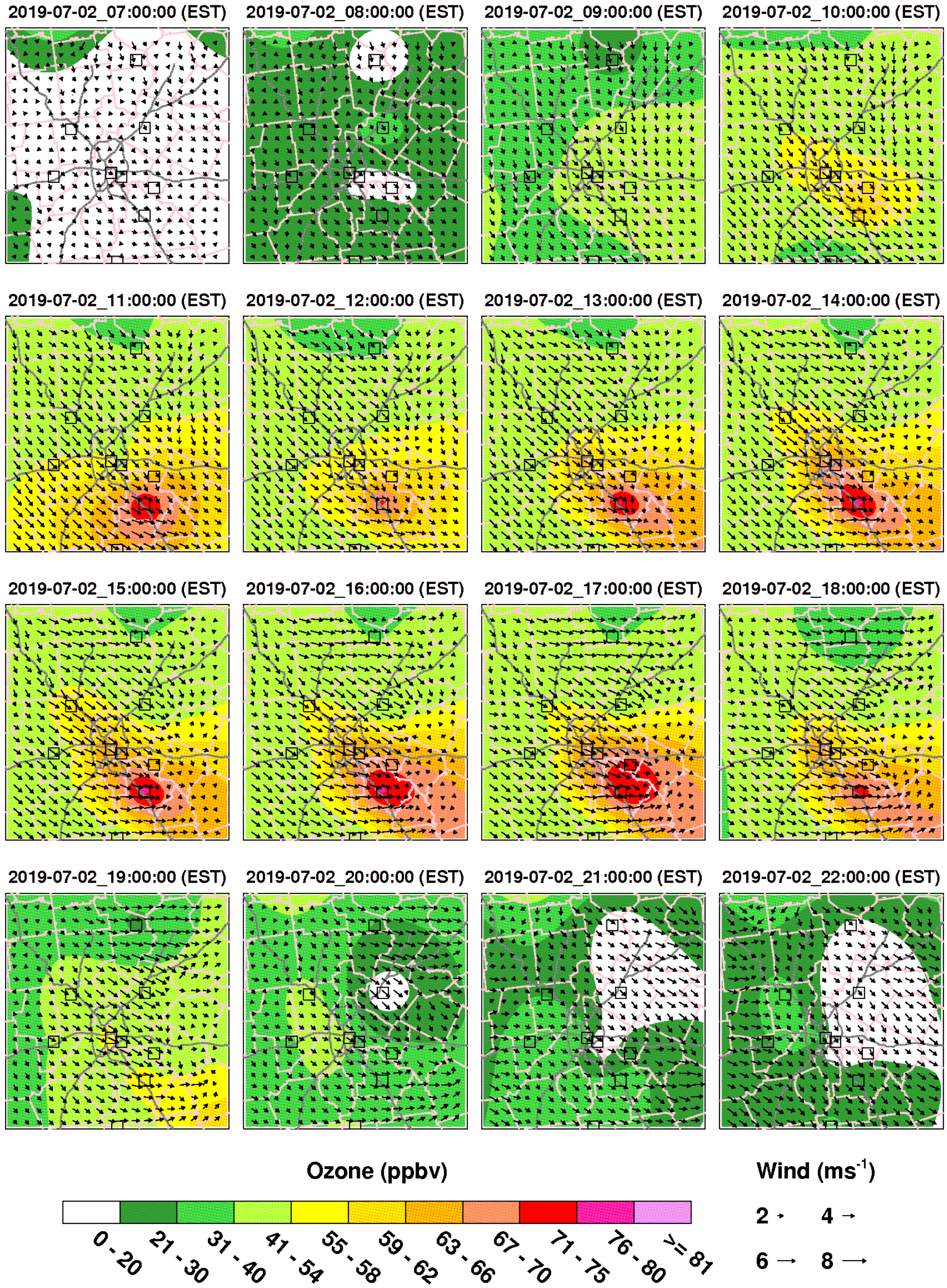

Figure A5. WRF simulated wind barbs and ozone observations (ppb) over the Metro Atlanta area from 7 AM to 10 PM on July 2, 2019. Ozone monitors are in black squares. The ozone exceedance occurred at the McDonough monitor.

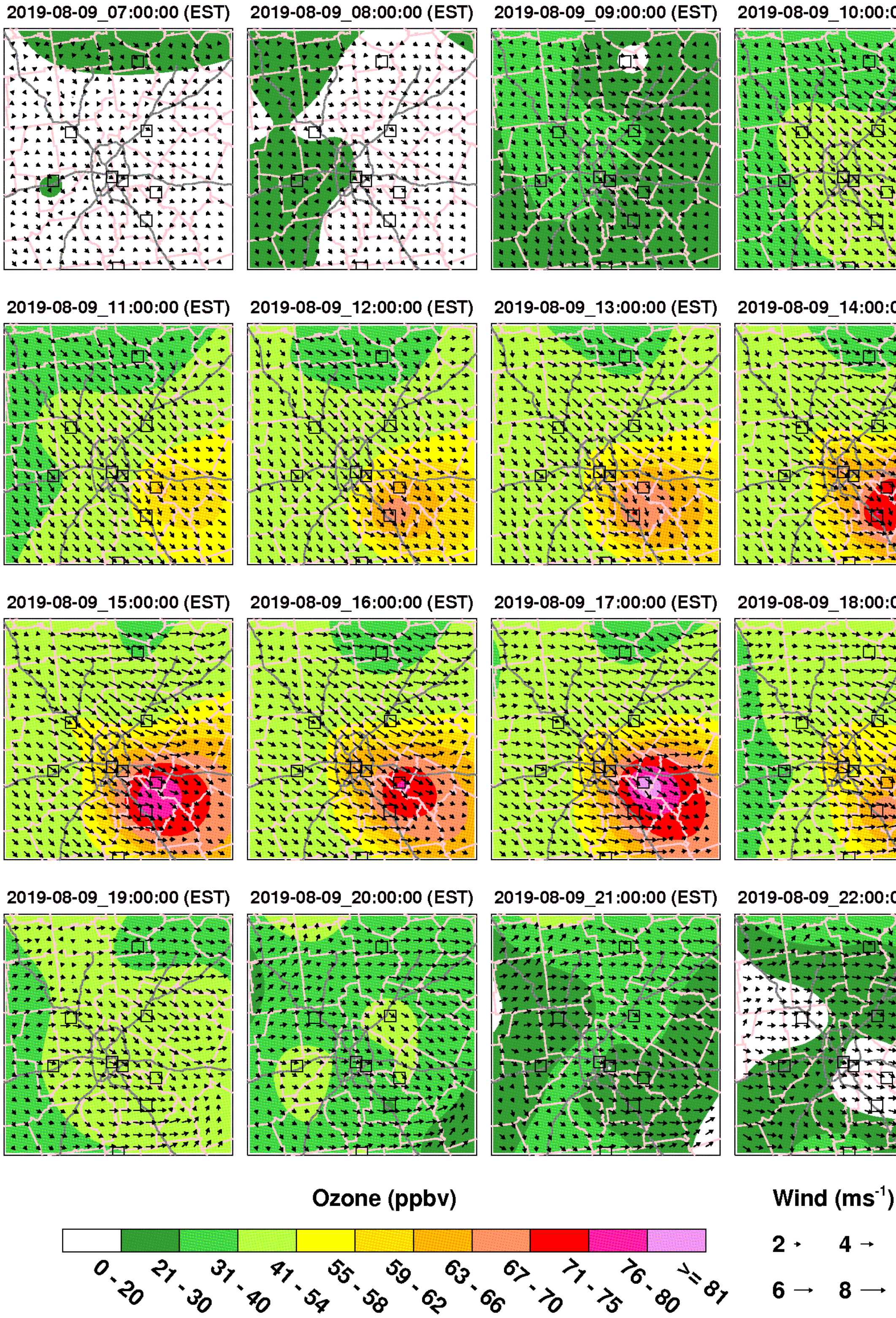

Figure A6. WRF simulated wind barbs and ozone observations (ppb) over the Metro Atlanta area from 7 AM to 10 PM on August 9, 2019. Ozone monitors are in black squares. The ozone exceedance occurred at Conyers and McDonough monitors.

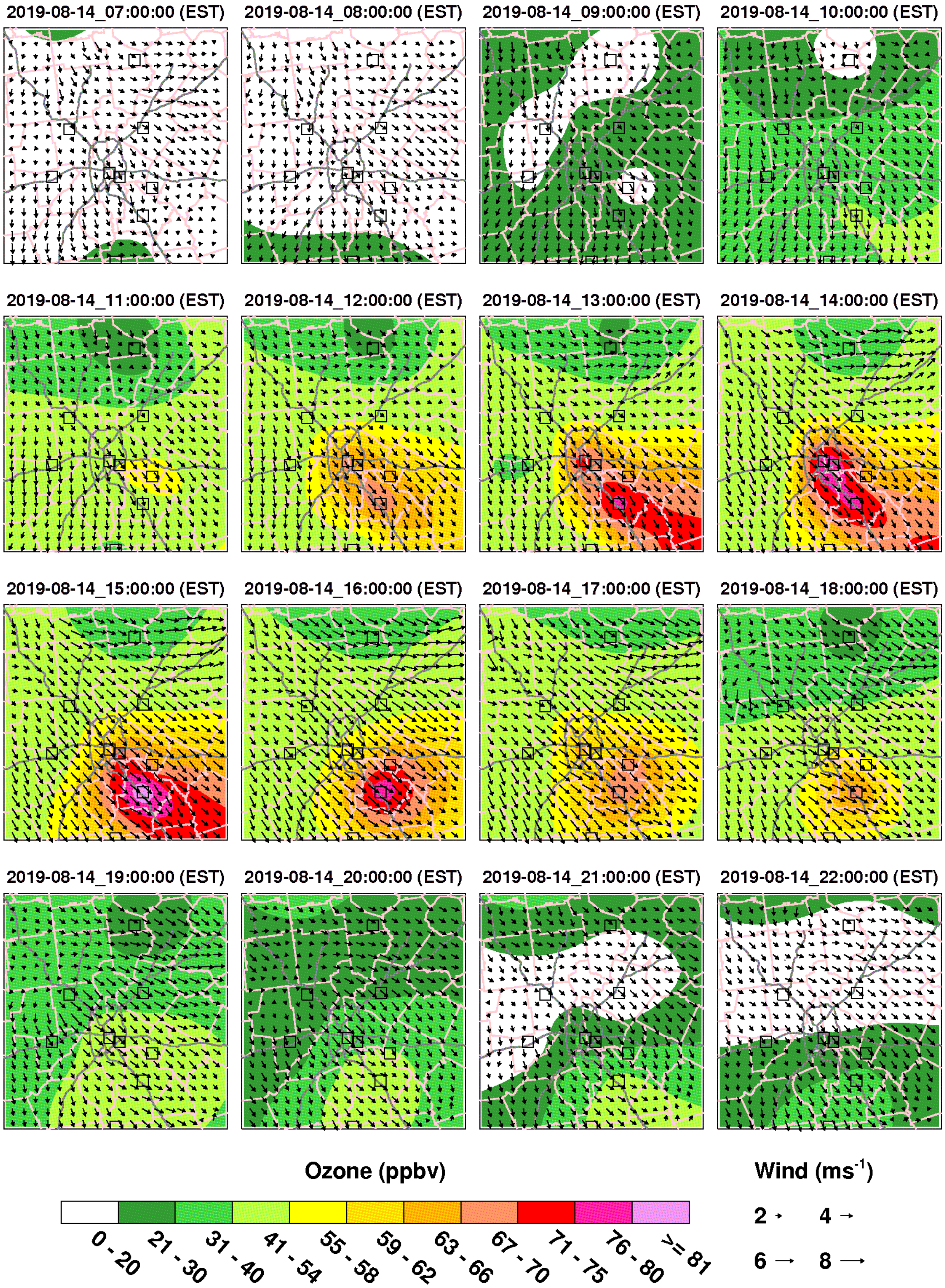

Figure A7. WRF simulated wind barbs and ozone observations (ppb) over the Metro Atlanta area from 7 AM to 10 PM on August 14, 2019. Ozone monitors are in black squares. The ozone exceedance occurred at the McDonough monitor.

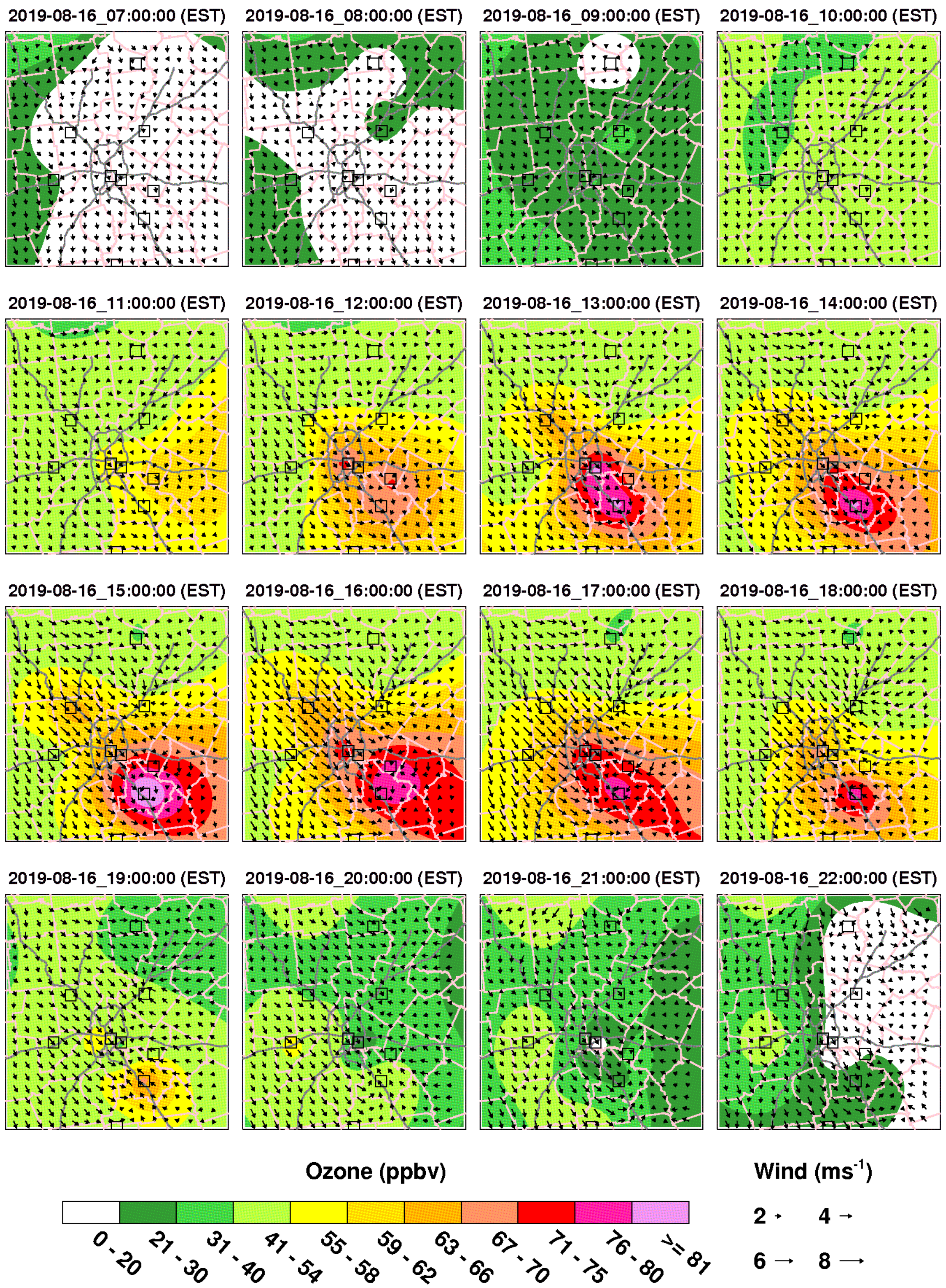

Figure A8. WRF simulated wind barbs and ozone observations (ppb) over the Metro Atlanta area from 7 AM to 10 PM on August 16, 2019. Ozone monitors are in black squares. The ozone exceedance occurred at the McDonough monitor.

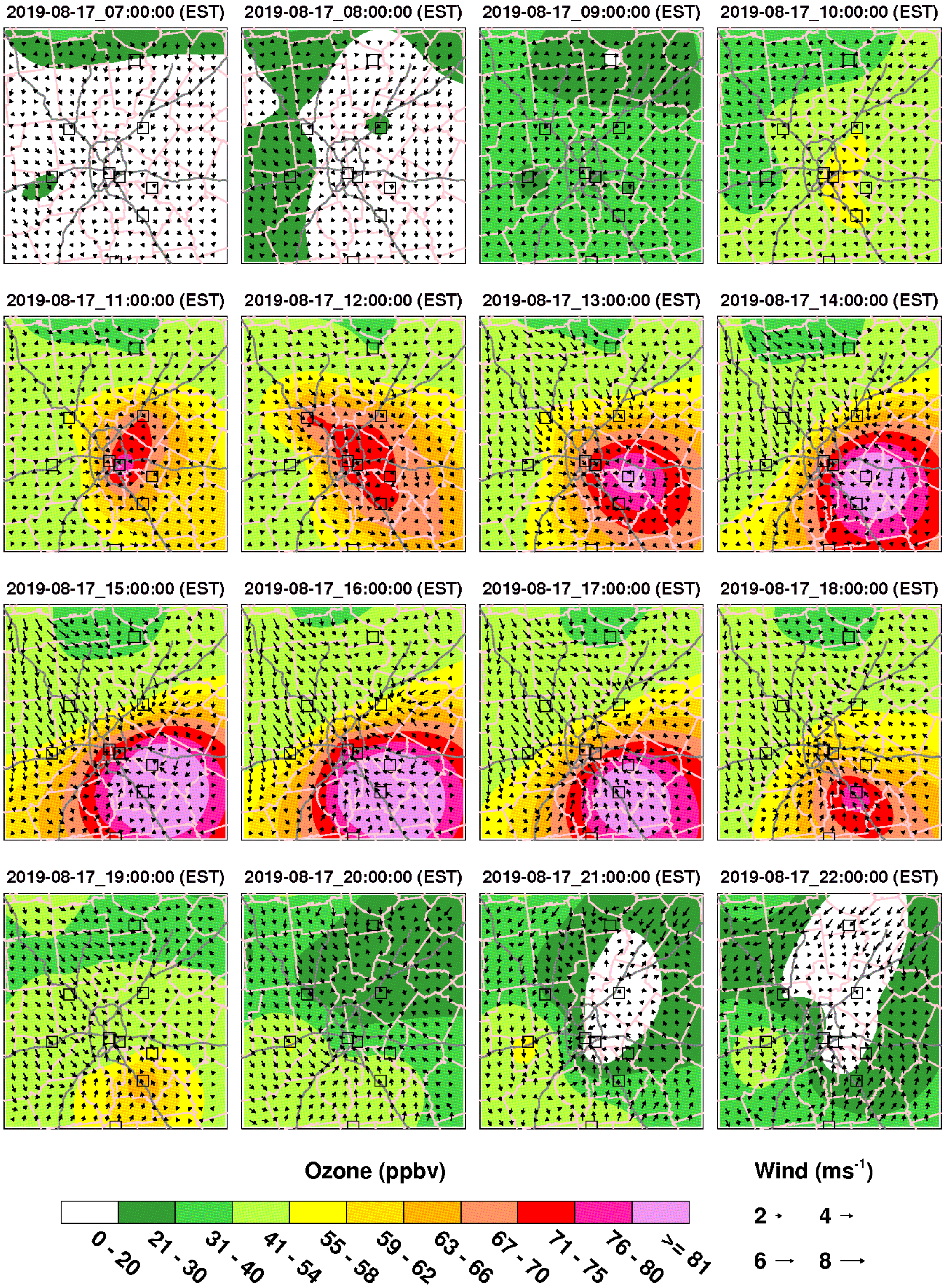

Figure A9. WRF simulated wind barbs and ozone observations (ppb) over the Metro Atlanta area from 7 AM to 10 PM on August 17, 2019. Ozone monitors are in black squares. The ozone exceedance occurred at McDonough, Conyers, and South DeKalb monitors.

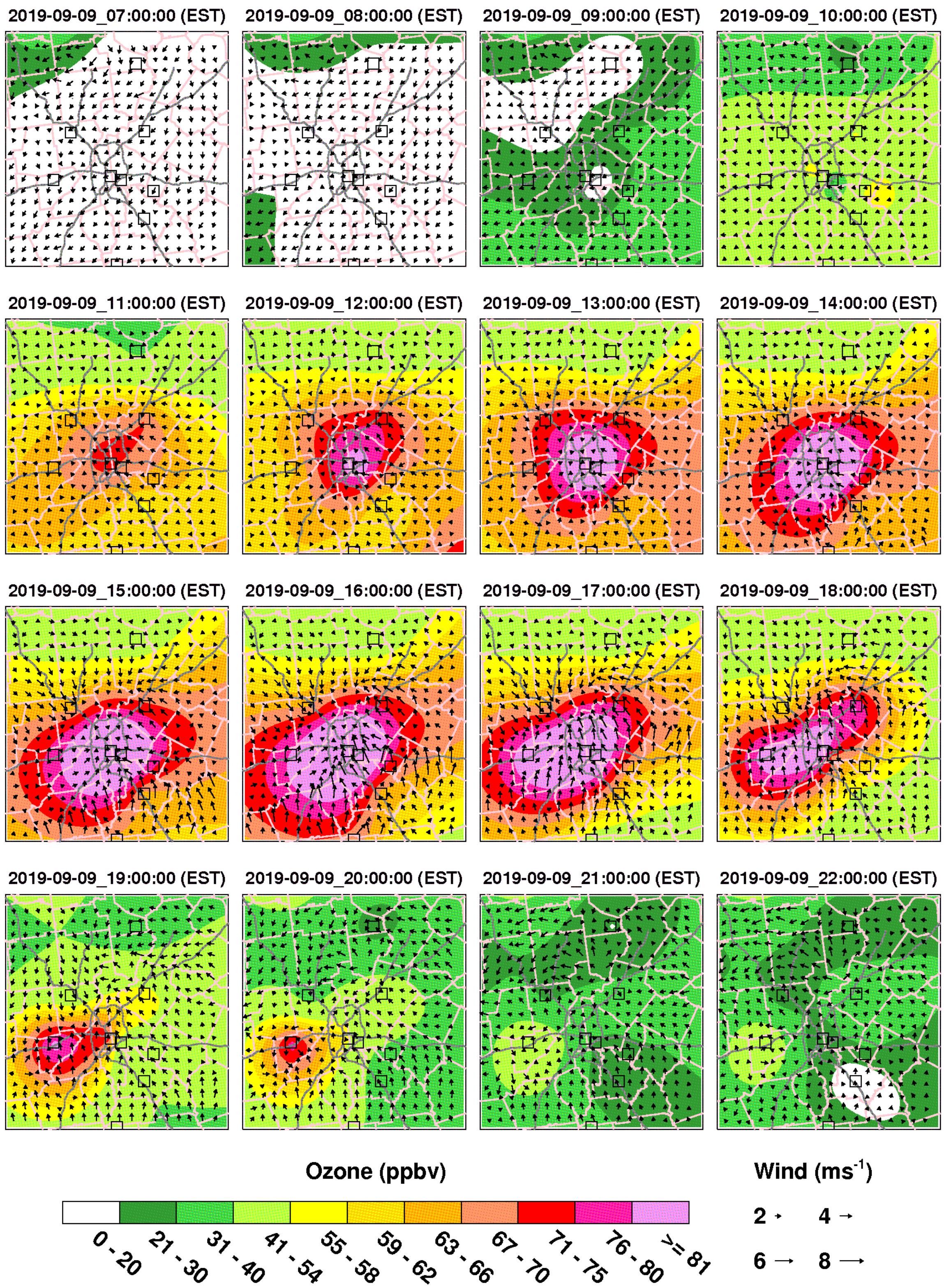

Figure A10. WRF simulated wind barbs and ozone observations (ppb) over the Metro Atlanta area from 7 AM to 10 PM on September 9, 2019. Ozone monitors are in black squares. The ozone exceedance occurred at United Ave., South DeKalb, Douglasville, and Gwinnett Tech monitors.

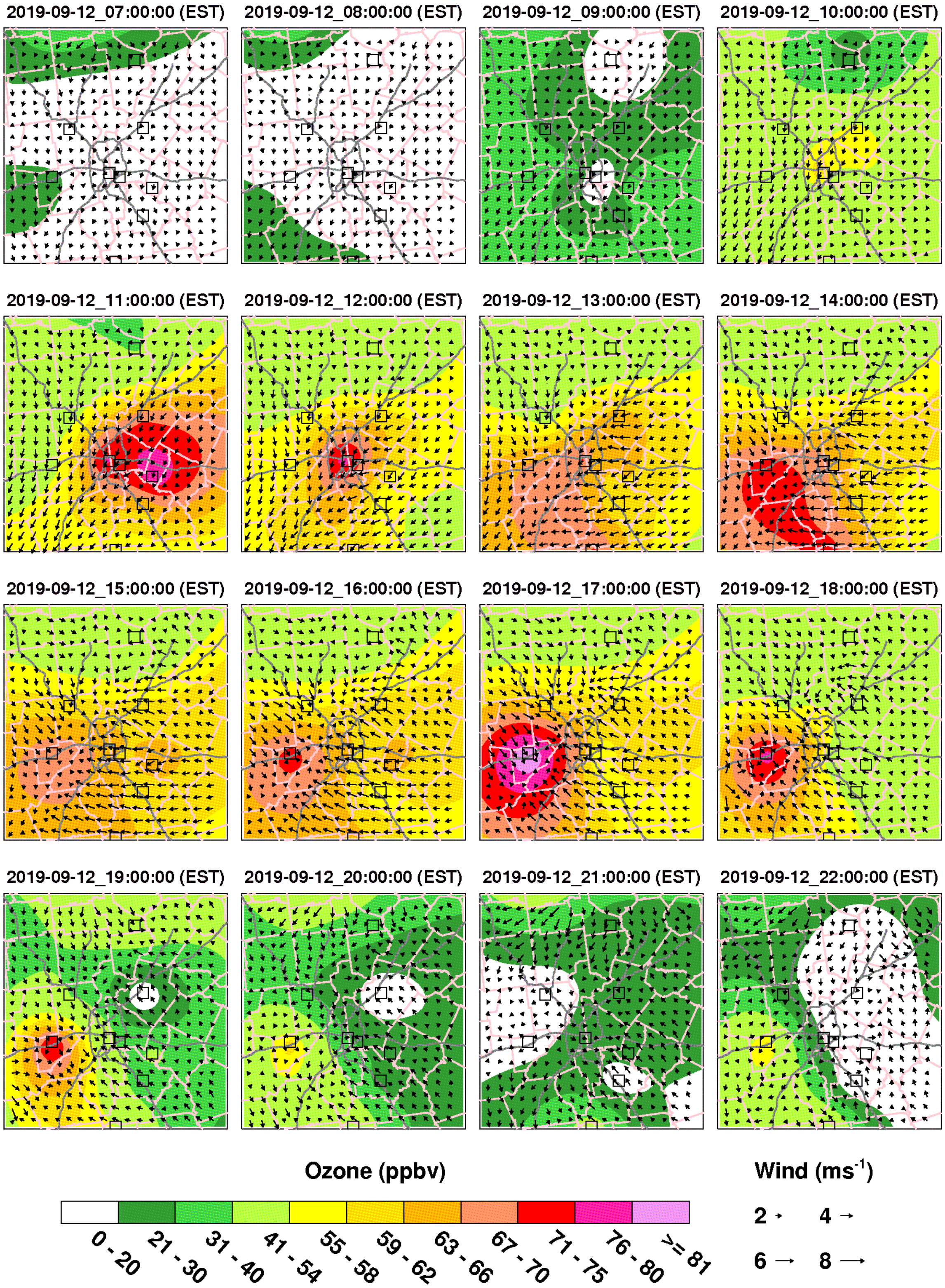

Figure A11. WRF simulated wind barbs and ozone observations (ppb) over the Metro Atlanta area from 7 AM to 10 PM on September 12, 2019. Ozone monitors are in black squares. The ozone exceedance occurred at the Douglasville monitor.

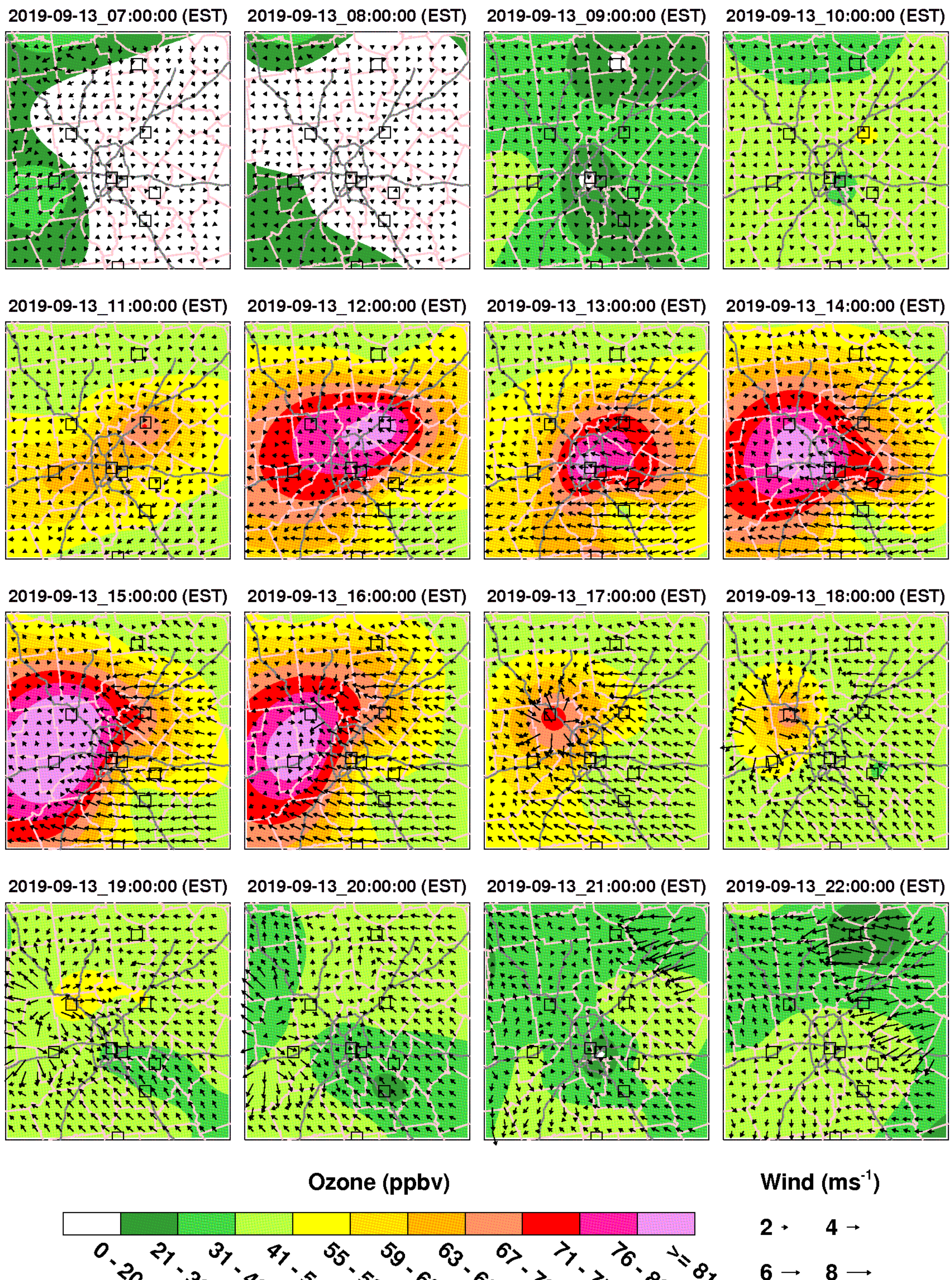

Figure A12. WRF simulated wind barbs and ozone observations (ppb) over the Metro Atlanta area from 7 AM to 10 PM on September 13, 2019. Ozone monitors are in black squares. The ozone exceedance occurred at the Kennesaw, Douglasville, and United Ave. monitors.

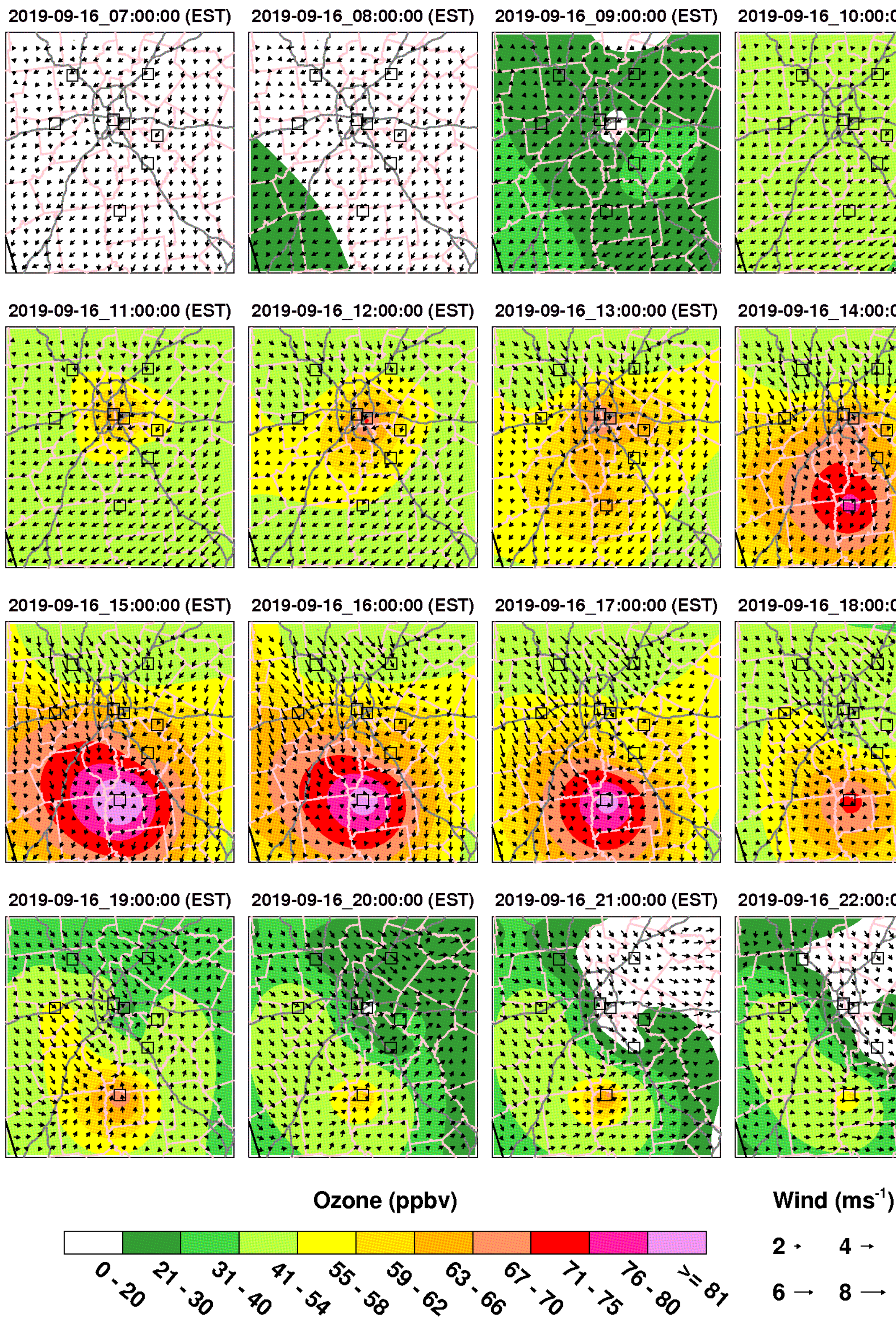

Figure A13. WRF simulated wind barbs and ozone observations (ppb) over the Metro Atlanta area from 7 AM to 10 PM on September 16, 2019. Ozone monitors are in black squares. The ozone exceedance occurred at the EPA CASTNET monitor.

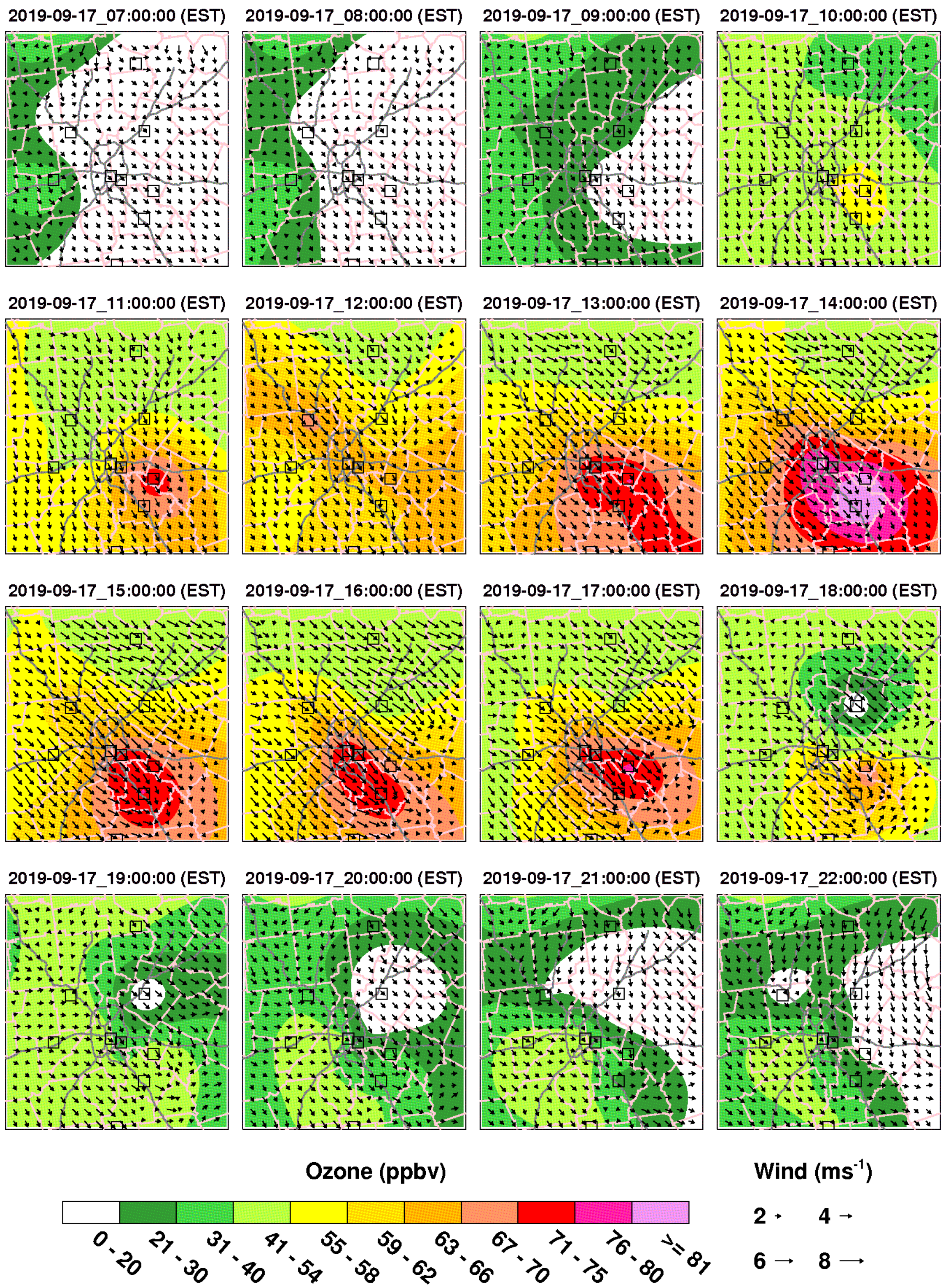

Figure A14. WRF simulated wind barbs and ozone observations (ppb) over the Metro Atlanta area from 7 AM to 10 PM on September 17, 2019. Ozone monitors are in black squares. The ozone exceedance occurred at Conyers, McDonough, and United Ave. monitors.

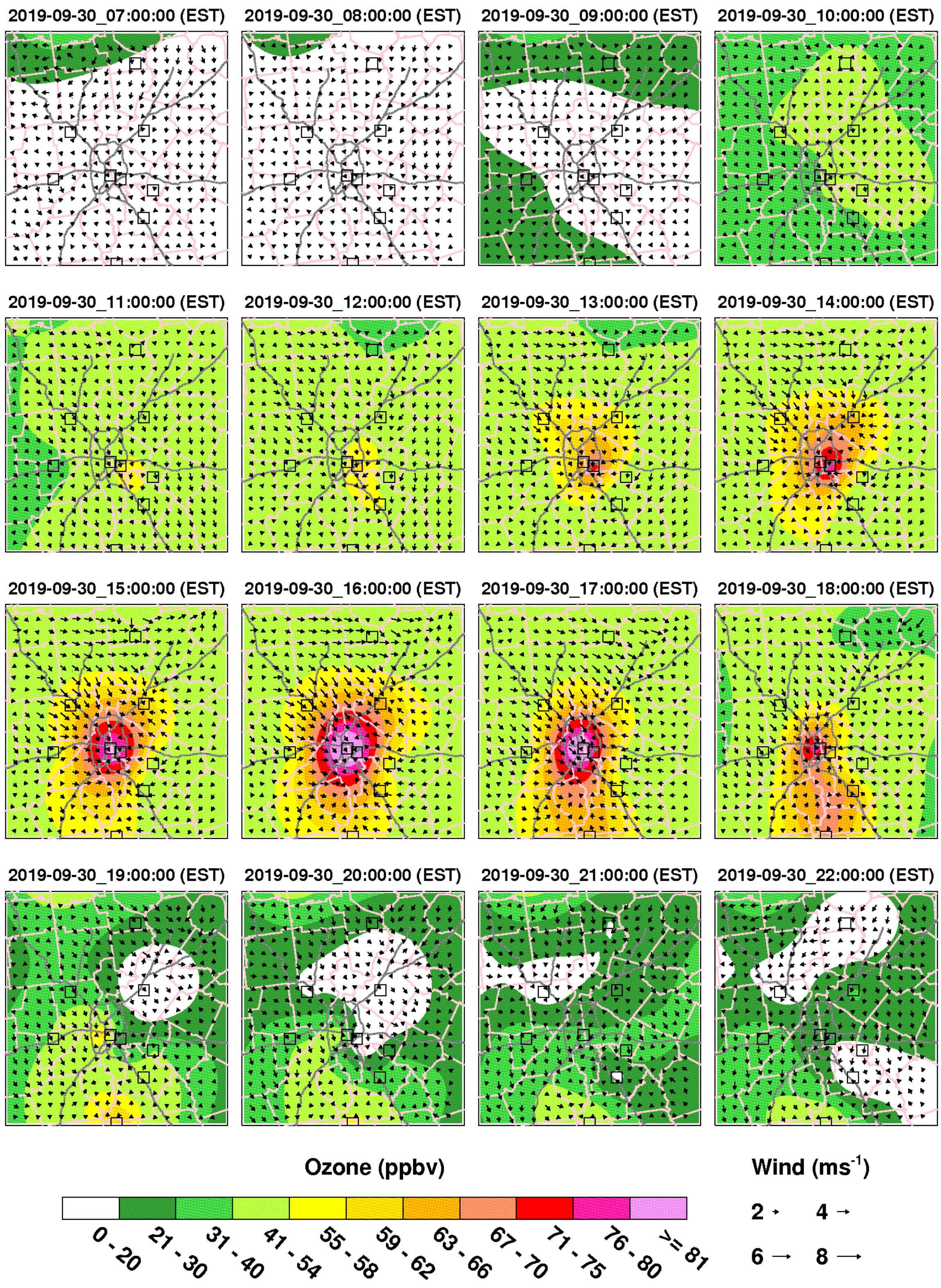

Figure A15. WRF simulated wind barbs and ozone observations (ppb) over the Metro Atlanta area from 7 AM to 10 PM on September 30, 2019. Ozone monitors are in black squares. The ozone exceedance occurred at the United Ave. monitor.

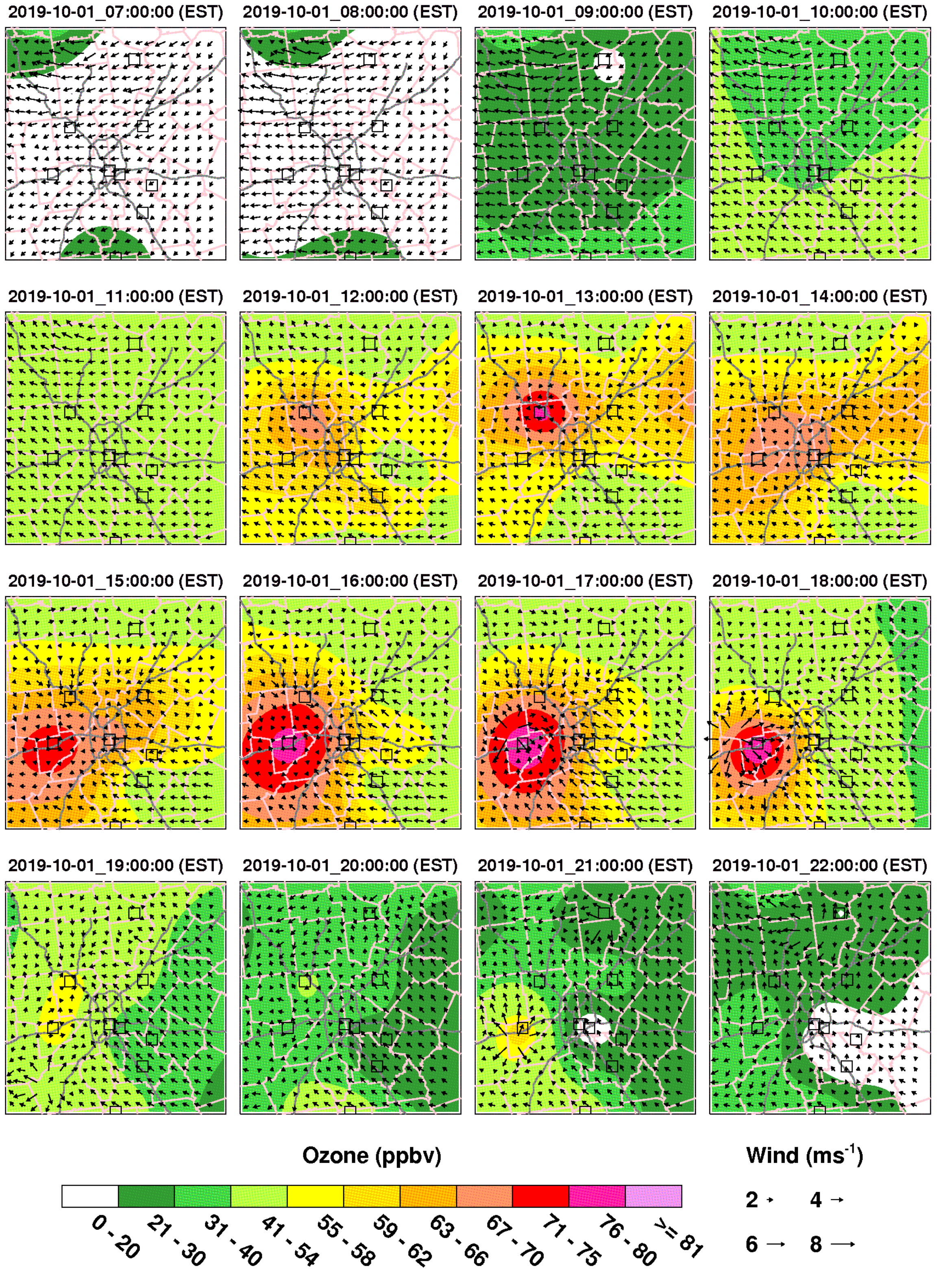

Figure A16. WRF simulated wind barbs and ozone observations (ppb) over the Metro Atlanta area from 7 AM to 10 PM on October 1, 2019. Ozone monitors are in black squares. The ozone exceedance occurred at the Douglasville monitor.

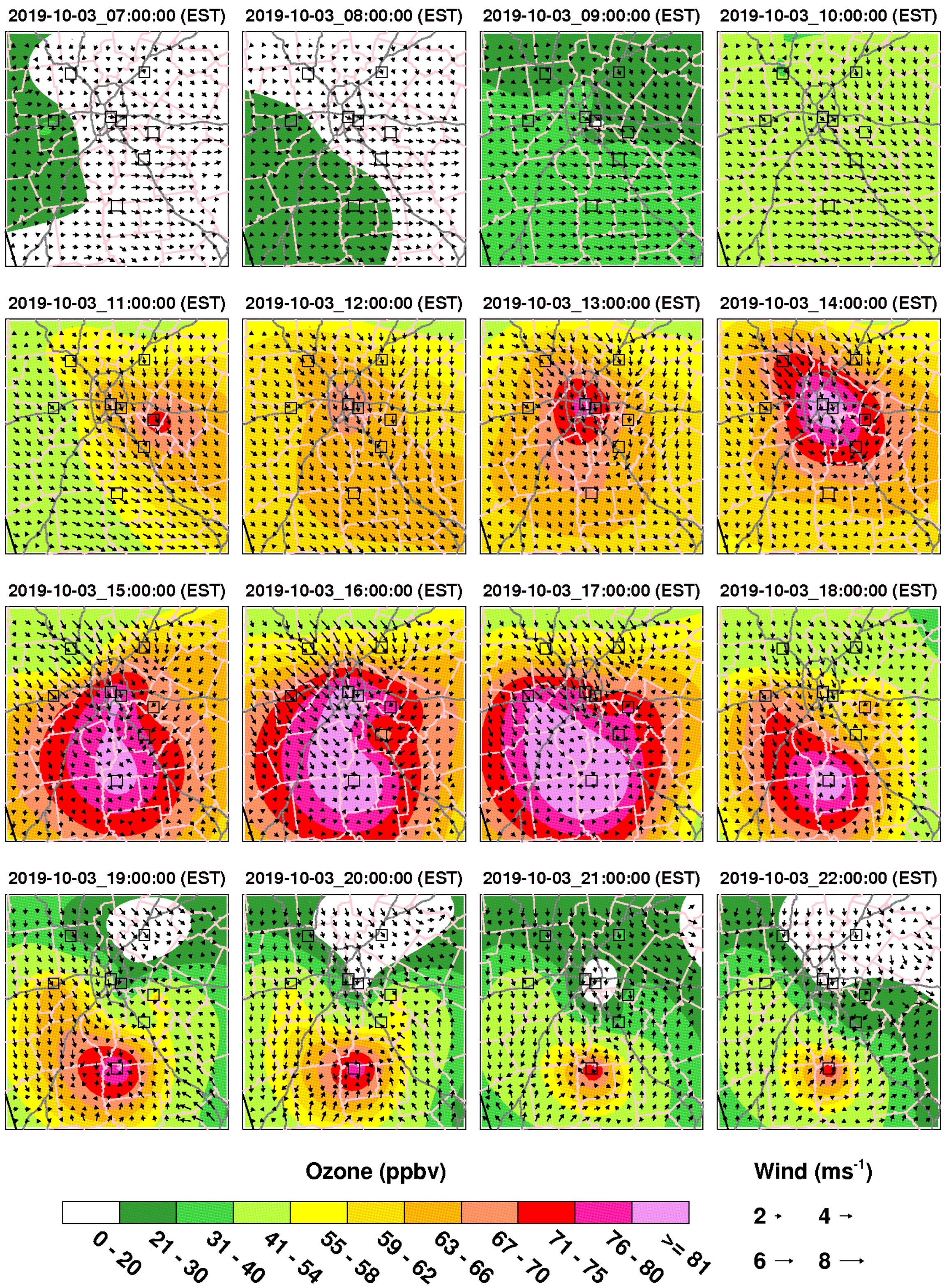

Figure A17. WRF simulated wind barbs and ozone observations (ppb) over the Metro Atlanta area from 7 AM to 10 PM on October 3, 2019. Ozone monitors are in black squares. The ozone exceedance occurred at EPA CASTNET, United Ave., South DeKalb, Conyers, and August monitors.

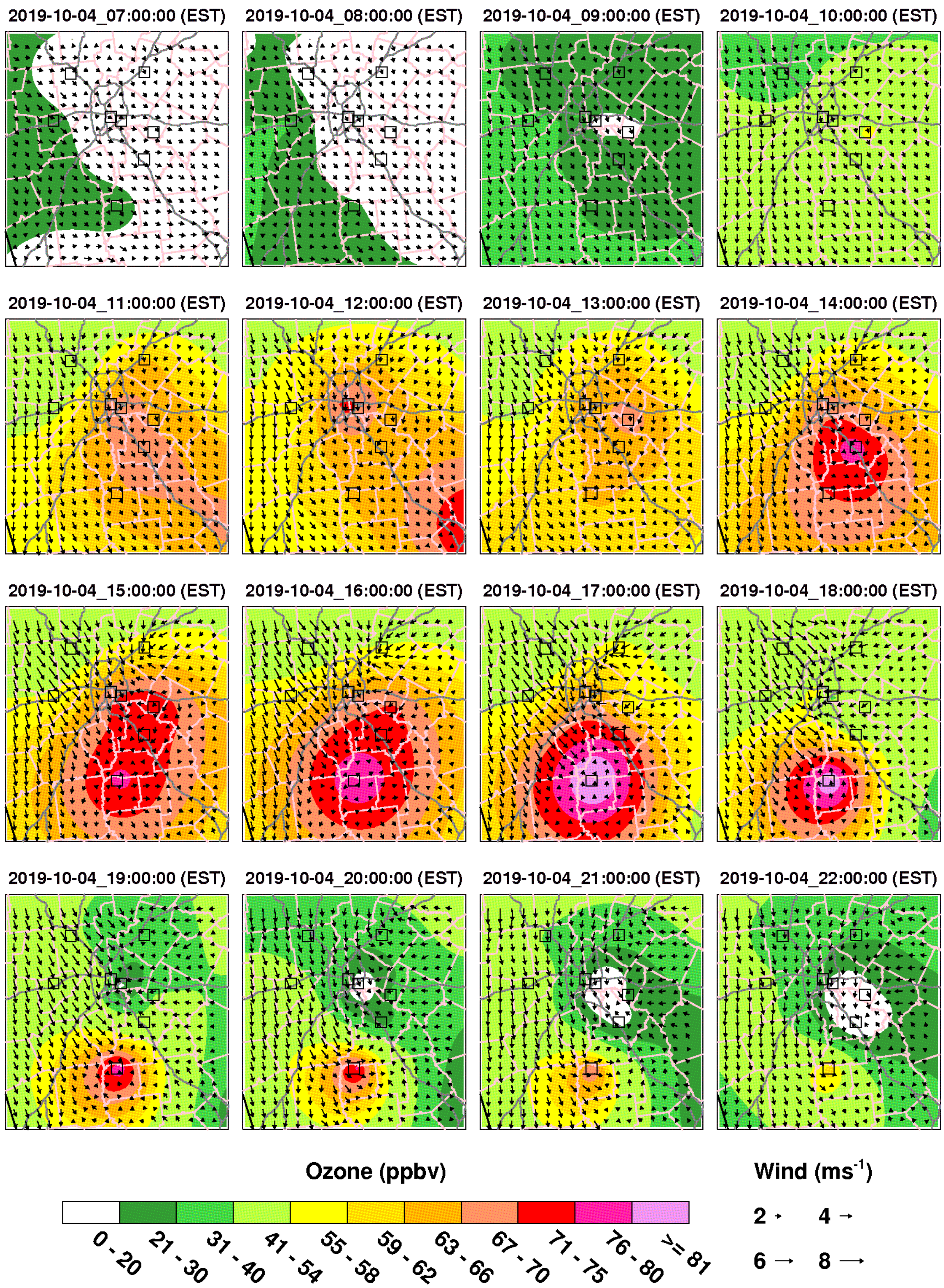

Figure A18. WRF simulated wind barbs and ozone observations (ppb) over the Metro Atlanta area from 7 AM to 10 PM on October 4, 2019. Ozone monitors are in black squares. The ozone exceedance occurred at EPA CASTNET and Augusta monitors.

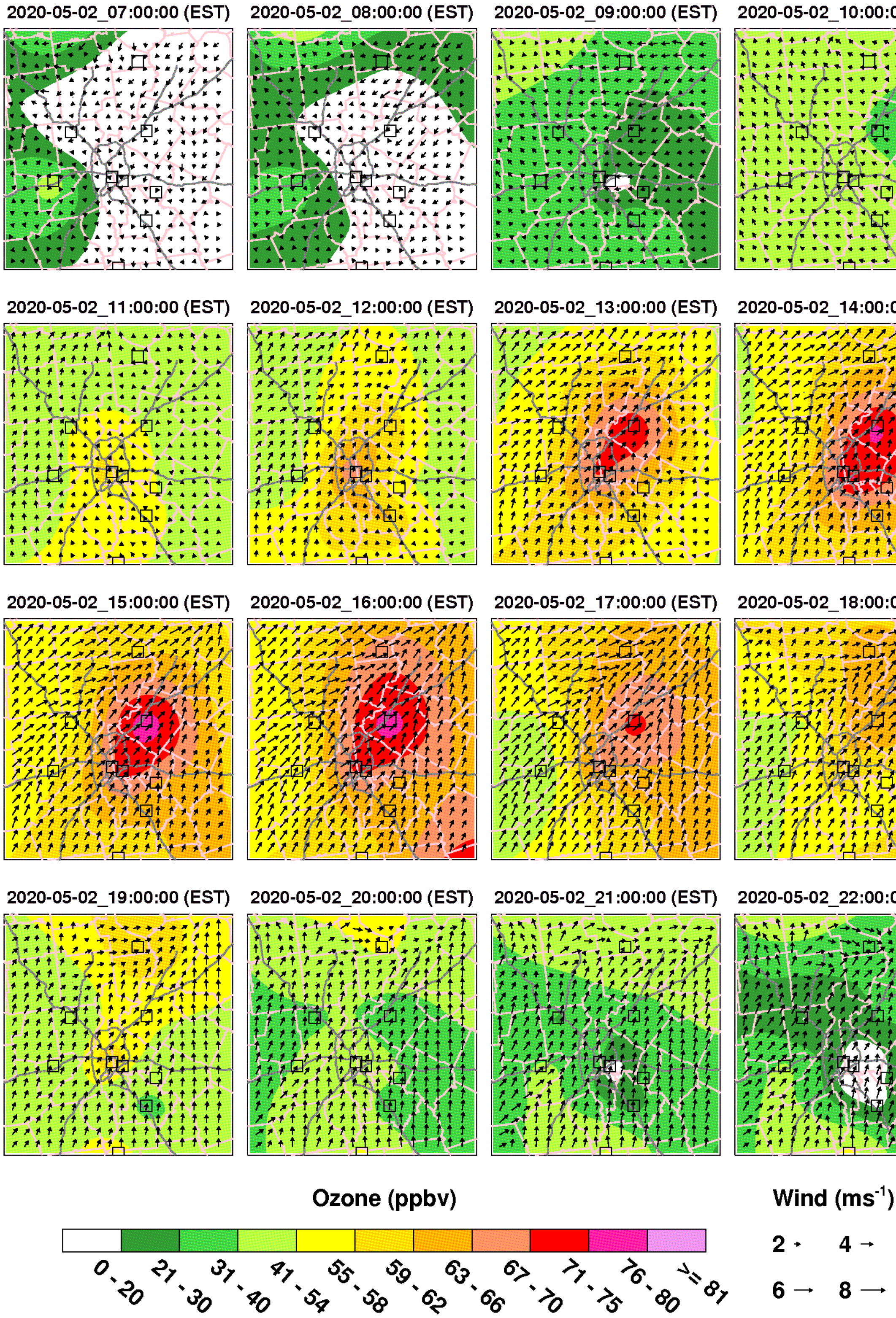

Figure A19. WRF simulated wind barbs and ozone observations (ppb) over the Metro Atlanta area from 7 AM to 10 PM on May 2, 2020. Ozone monitors are in black squares. The ozone exceedance occurred at the Gwinnett Tech monitor.

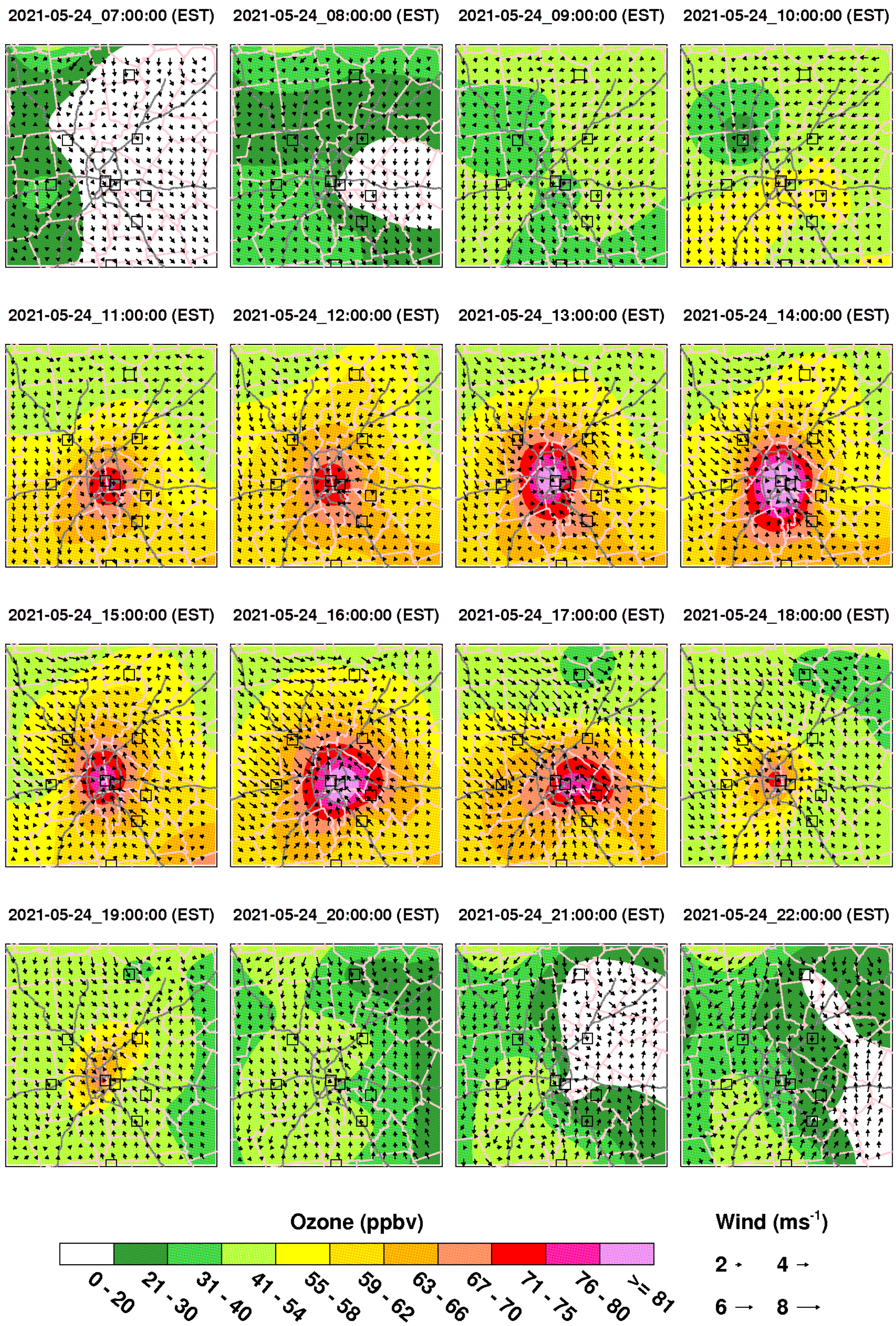

Figure A20. WRF simulated wind barbs and ozone observations (ppb) over the Metro Atlanta area from 7 AM to 10 PM on May 24, 2021. Ozone monitors are in black squares. The ozone exceedance occurred at United Ave. and South DeKalb monitors.

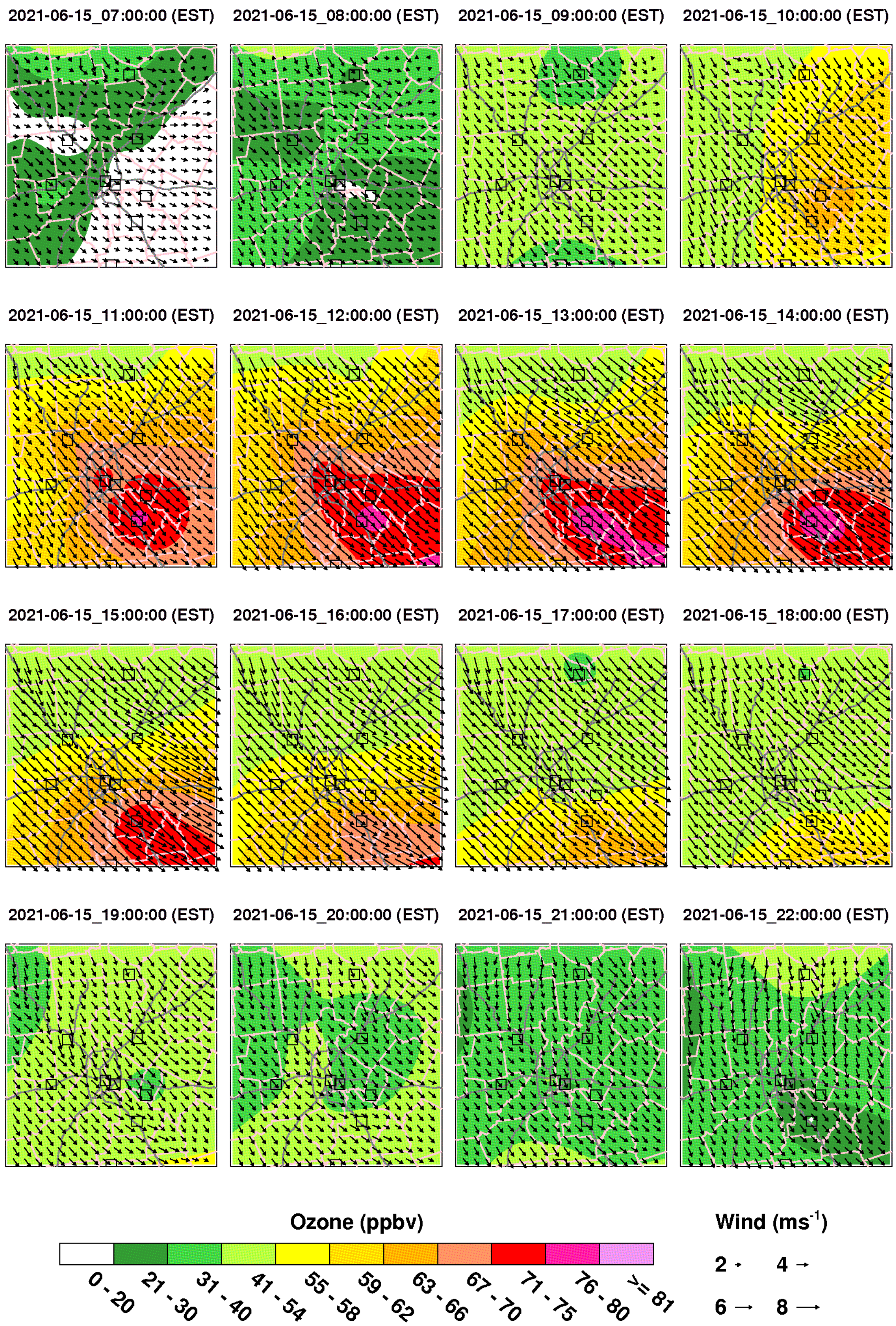

Figure A21. WRF simulated wind barbs and ozone observations (ppb) over the Metro Atlanta area from 7 AM to 10 PM on June 15, 2021. Ozone monitors are in black squares. The ozone exceedance occurred at McDonough and Macon-Forestry monitors.

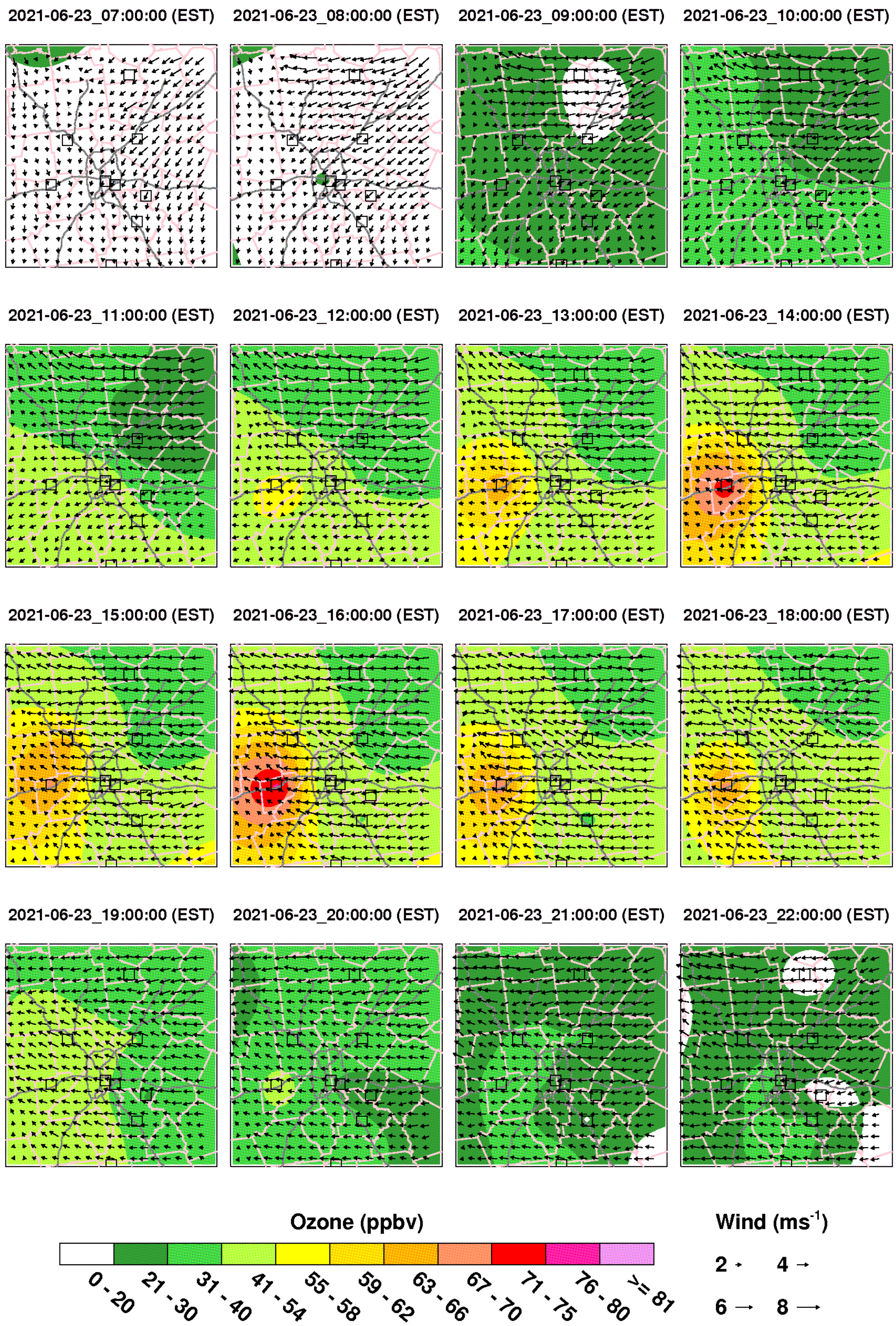

Figure A22. WRF simulated wind barbs and ozone observations (ppb) over the Metro Atlanta area from 7 AM to 10 PM on June 23, 2021. Ozone monitors are in black squares. The ozone exceedance occurred at the Douglasville monitor.

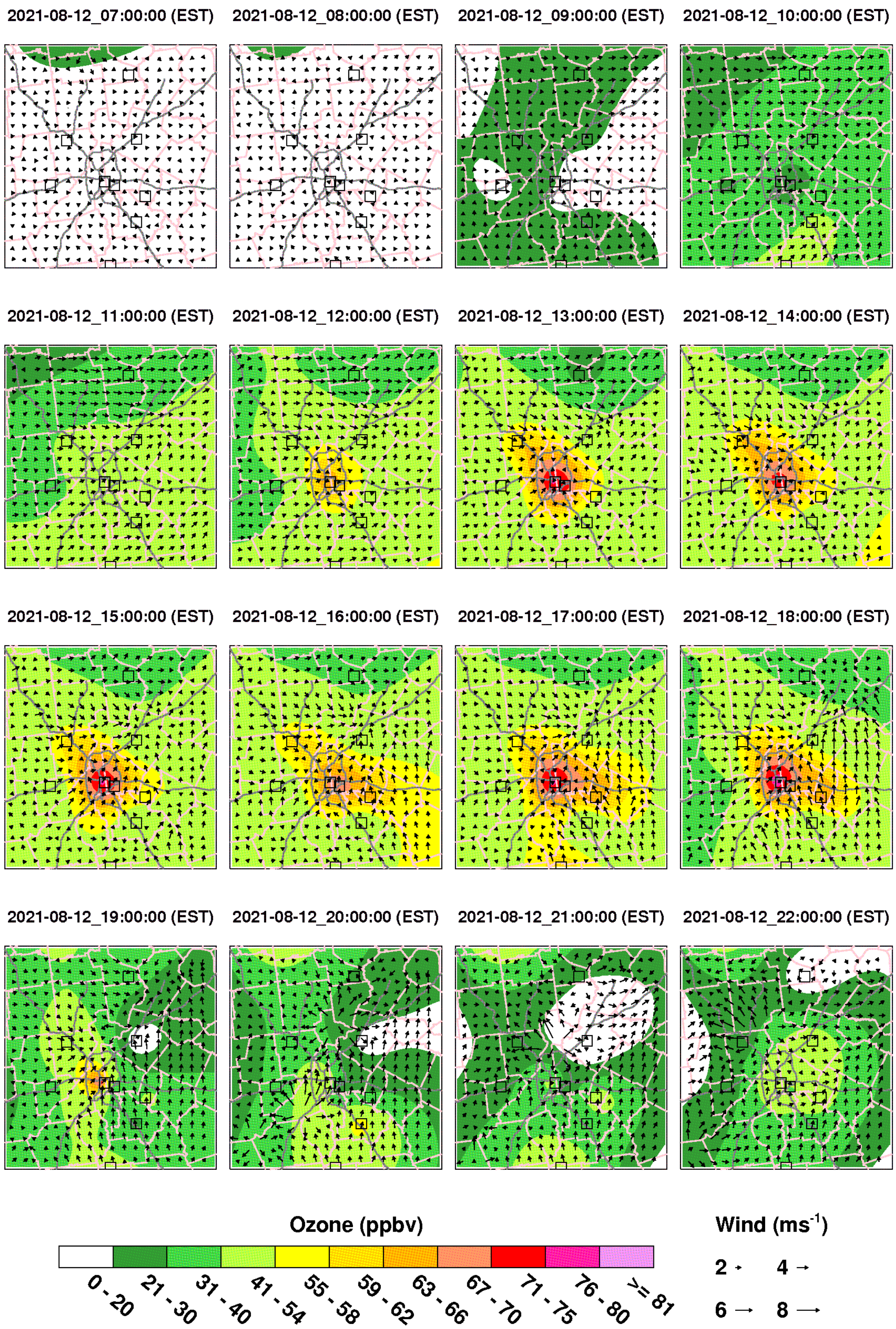

Figure A23. WRF simulated wind barbs and ozone observations (ppb) over the Metro Atlanta area from 7 AM to 10 PM on August 12, 2021. Ozone monitors are in black squares. The ozone exceedance occurred at the United Ave. monitor.

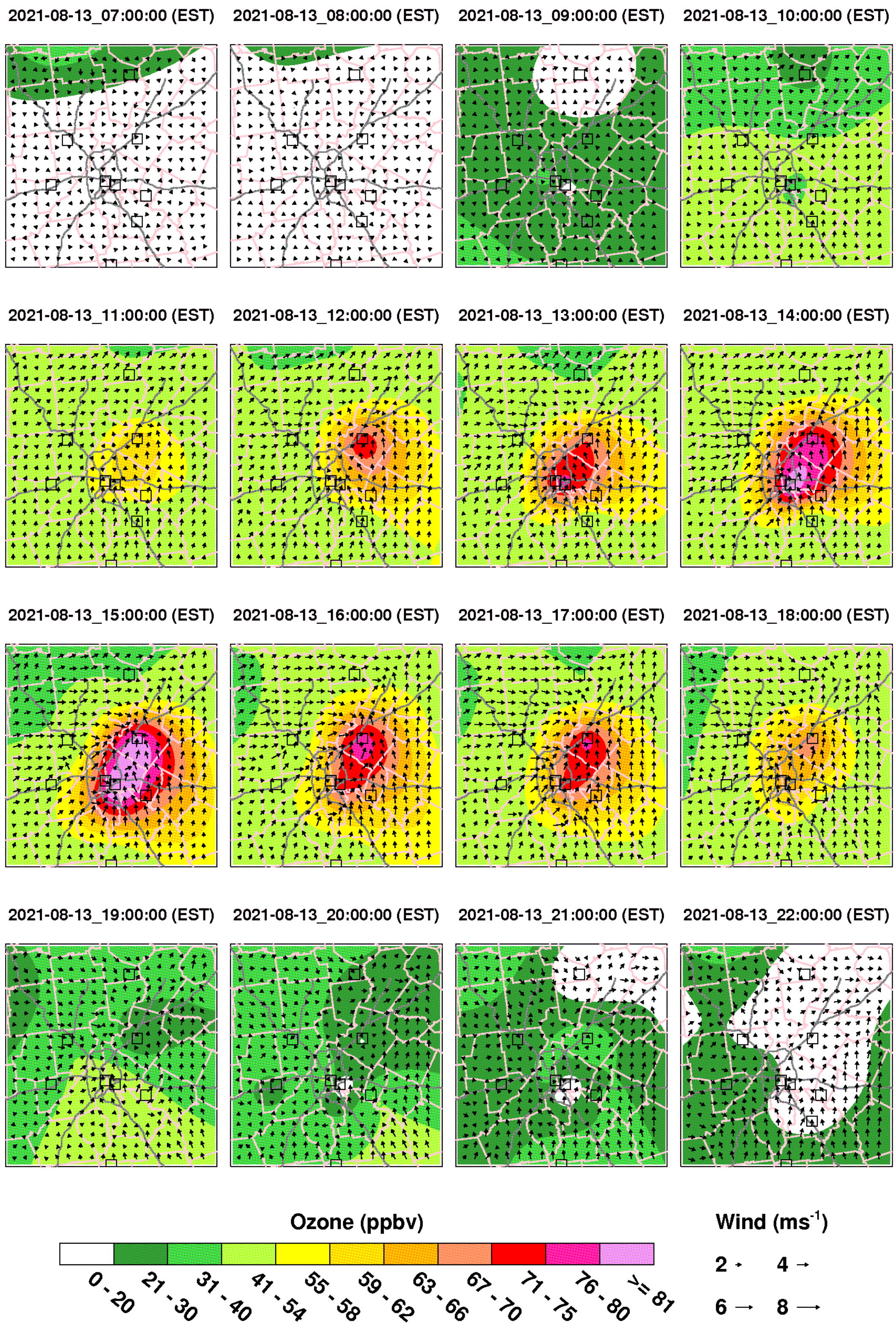

Figure A24. WRF simulated wind barbs and ozone observations (ppb) over the Metro Atlanta area from 7 AM to 10 PM on August 13, 2021. Ozone monitors are in black squares. The ozone exceedance occurred at South DeKalb and Gwinnett Tech monitors.

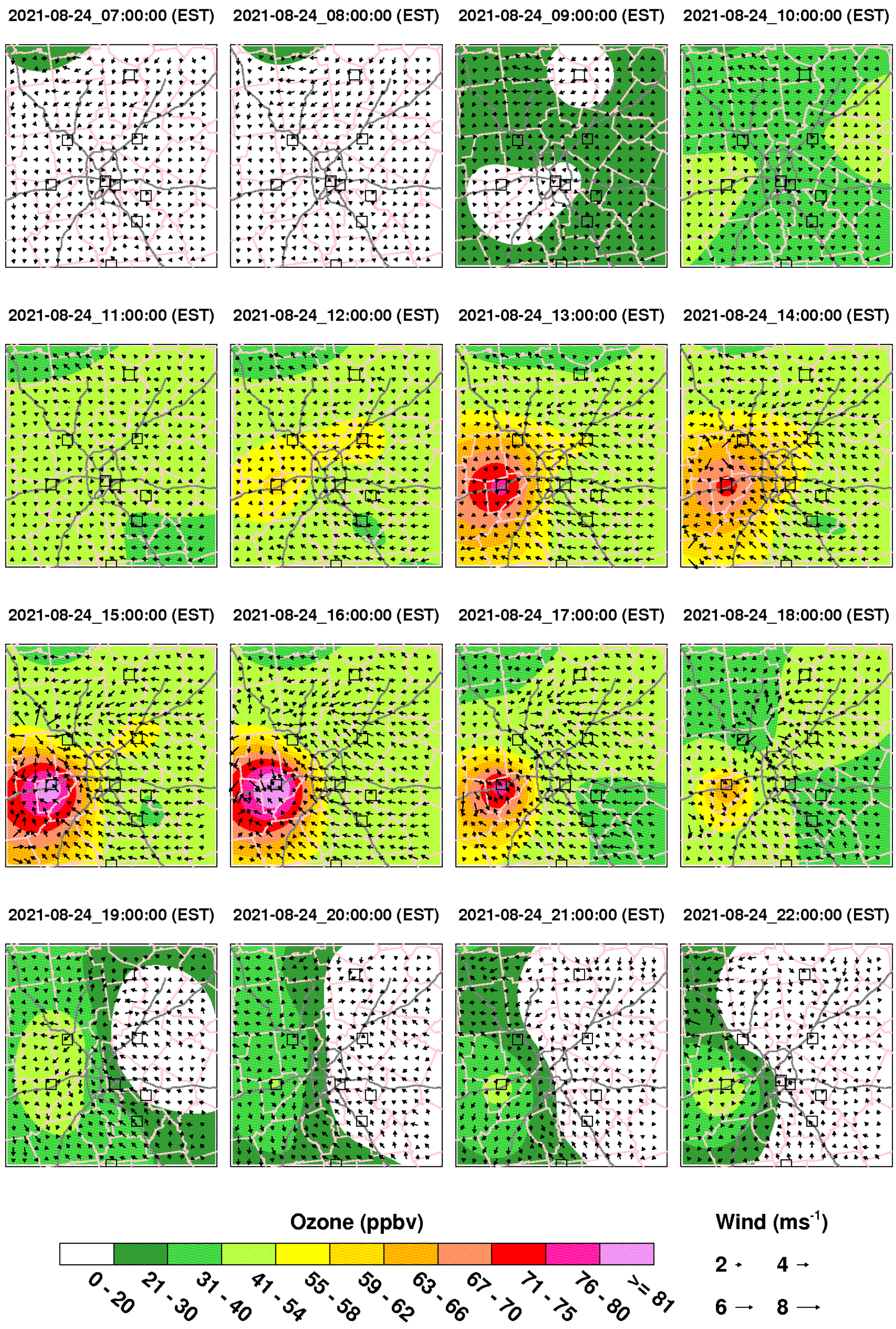

Figure A25. WRF simulated wind barbs and ozone observations (ppb) over the Metro Atlanta area from 7 AM to 10 PM on August 24, 2021. Ozone monitors are in black squares. The ozone exceedance occurred at the Douglasville monitor.

Appendix B

Monthly TROPOMI NO_2 VCDs in June, July, and August during 2019, 2020, and 2021 over the Metro Atlanta area

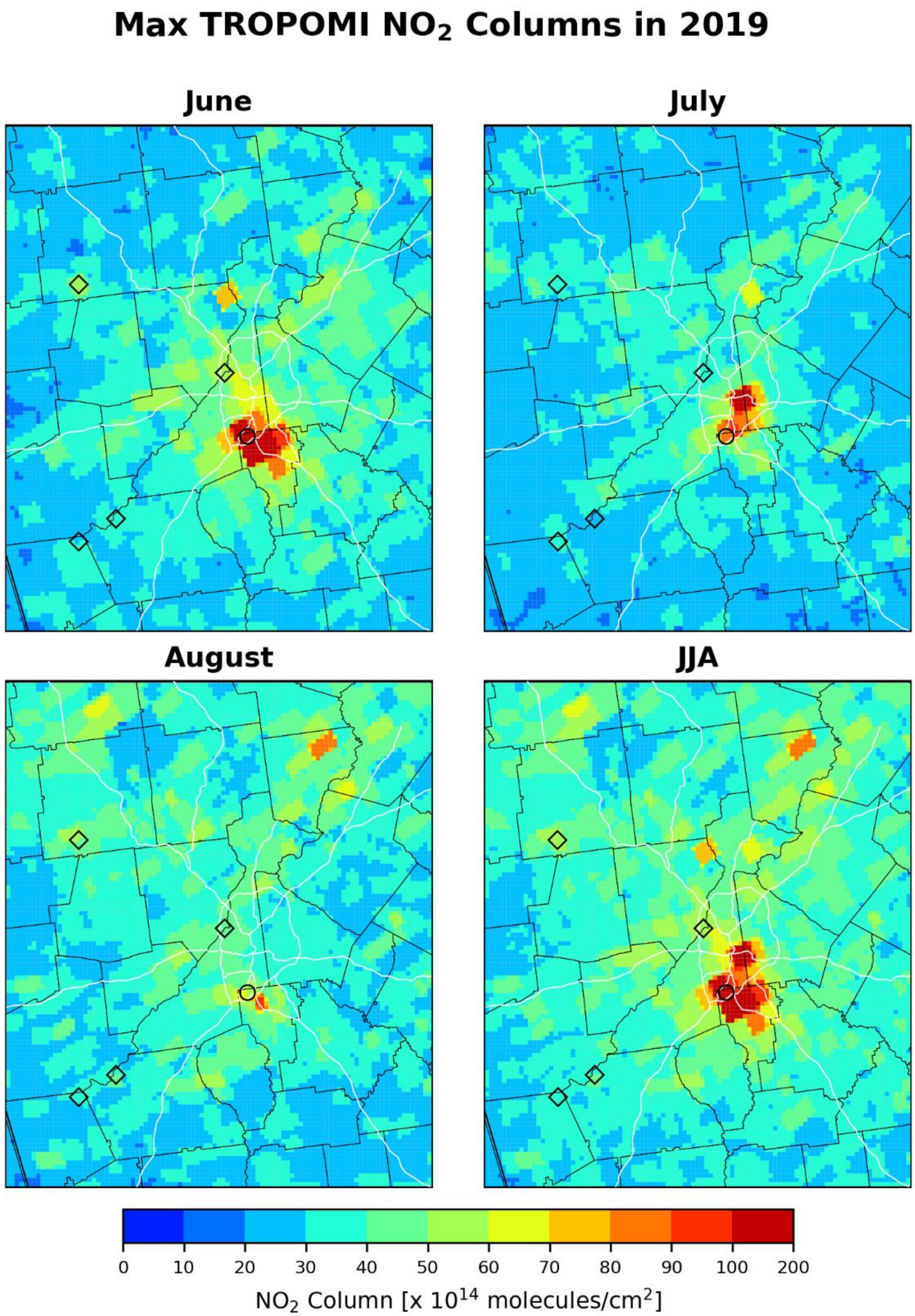

Figure B1. Maximum TROPOMI Tropospheric NO_2 columns over the Metro Atlanta area in June, July, August, and June-August during 2019.

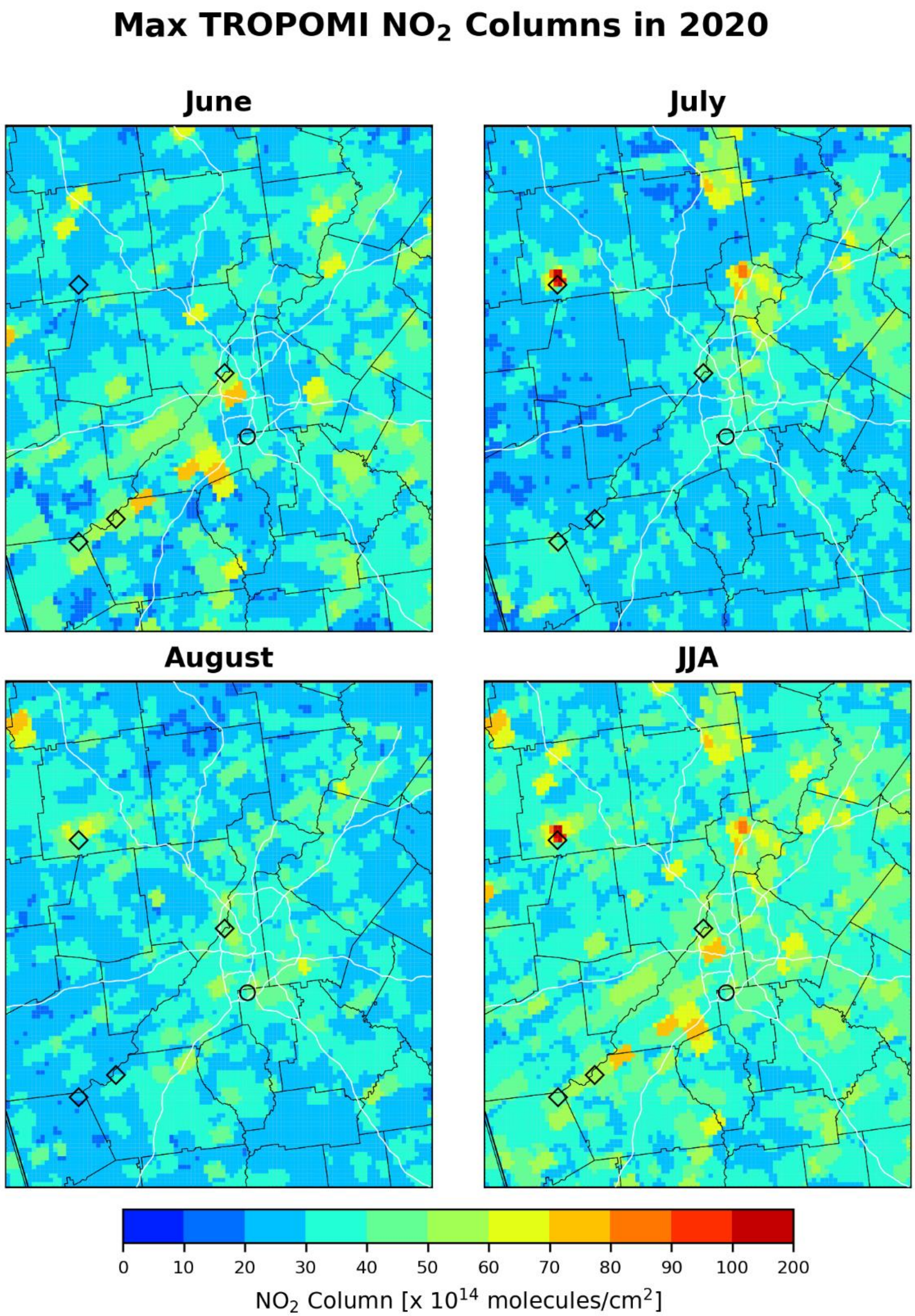

Figure B2. Maximum TROPOMI Tropospheric NO_2 columns over the Metro Atlanta area in June, July, August, and June-August during 2020.

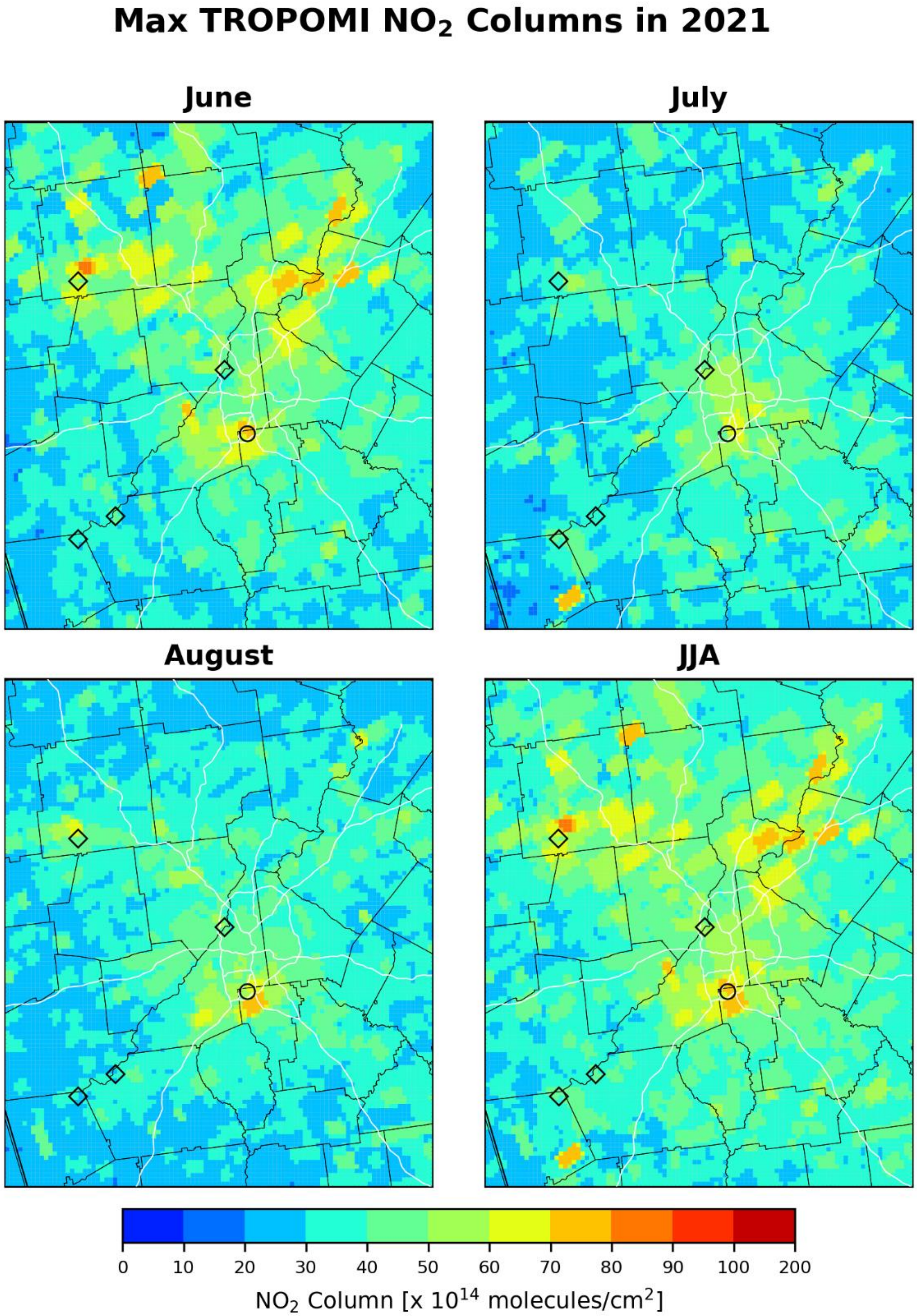

Figure B3. Maximum TROPOMI Tropospheric NO_2 columns over the Metro Atlanta area in June, July, August, and June-August during 2021.

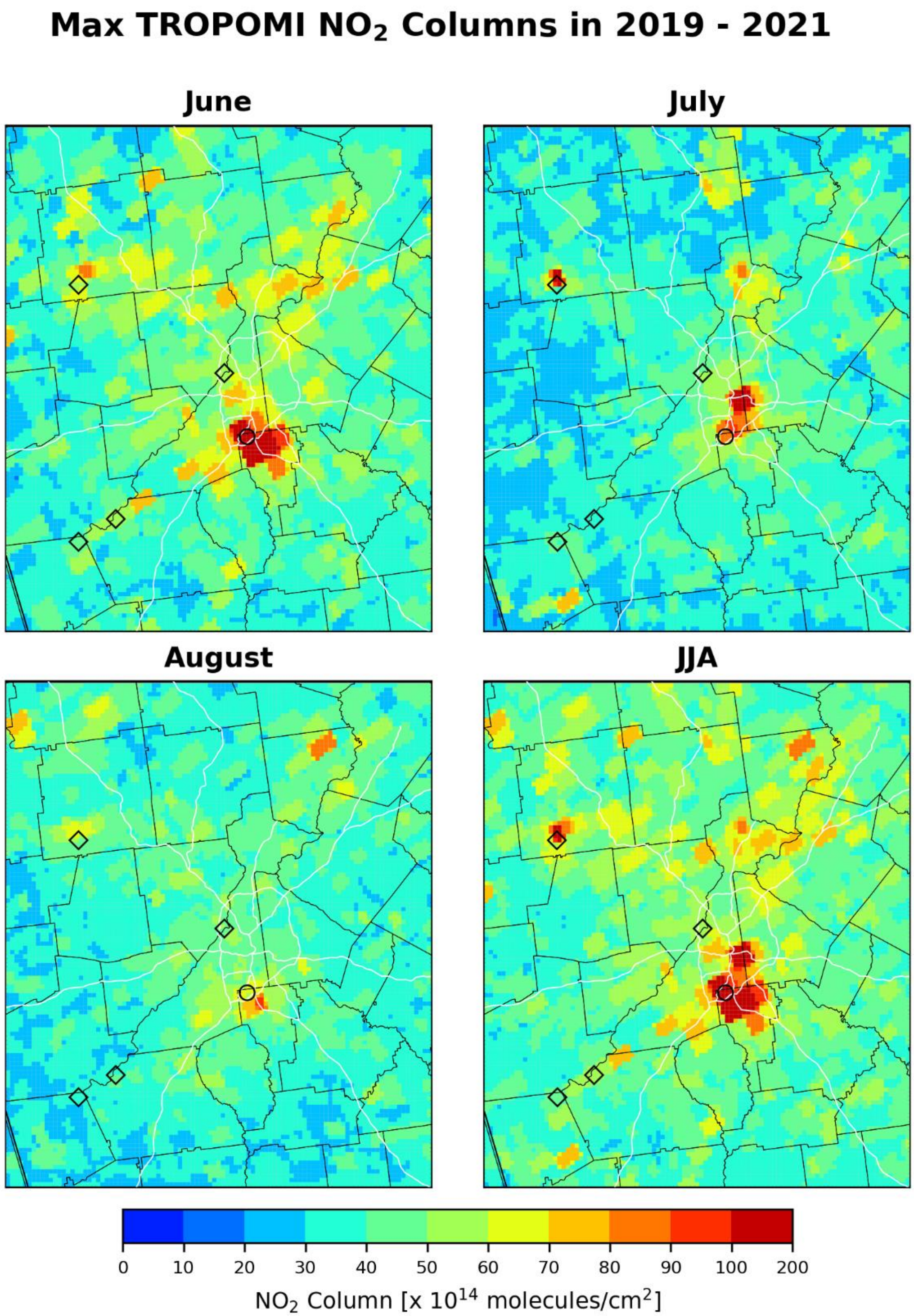

Figure B4. Maximum TROPOMI Tropospheric NO_2 columns over the Metro Atlanta area in June, July, August, and June-August during 2019-2021.

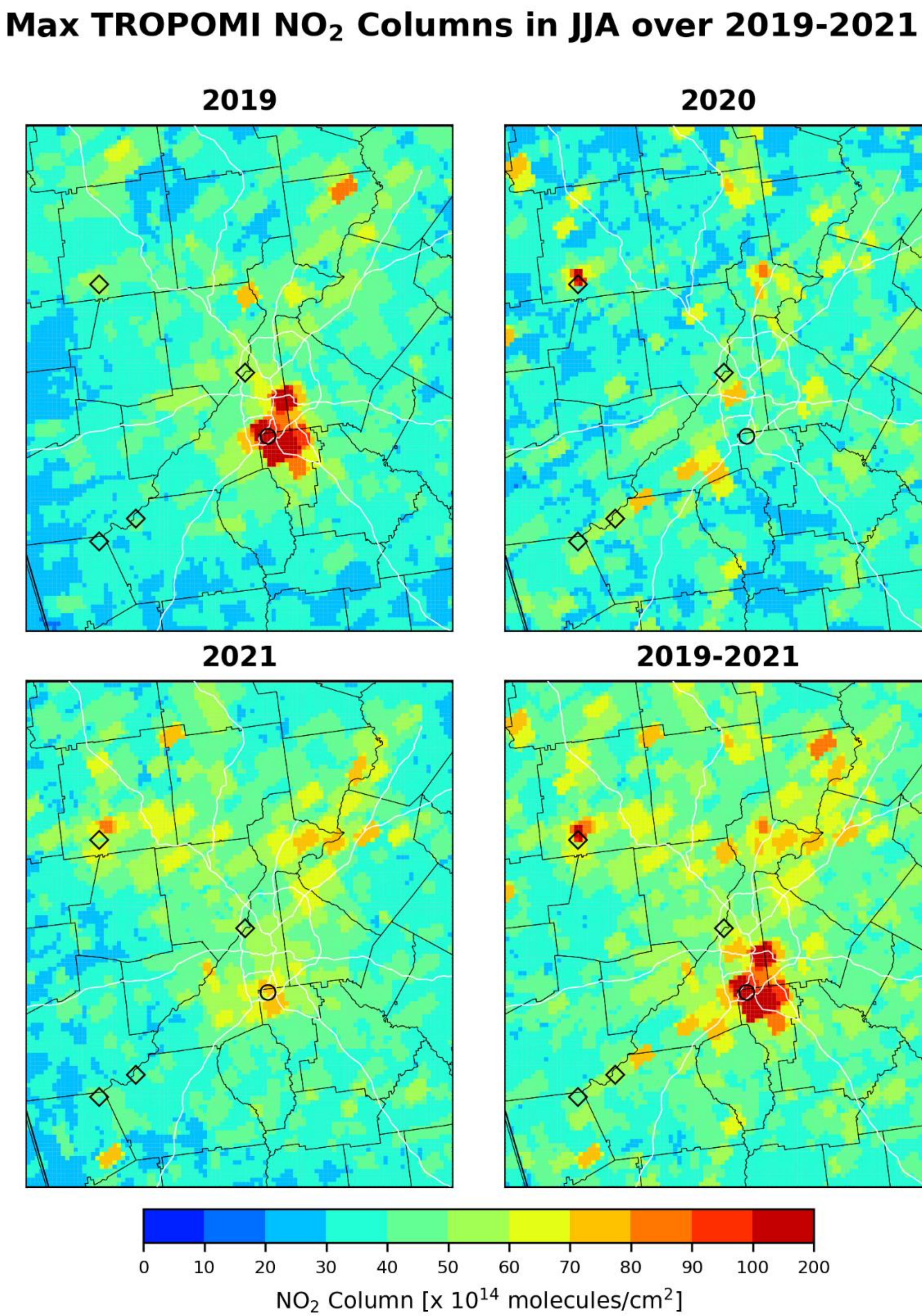

Figure B5. Maximum TROPOMI Tropospheric NO_2 columns over the Metro Atlanta area in June-August during 2019, 2020, 2021, and 2019-2021.

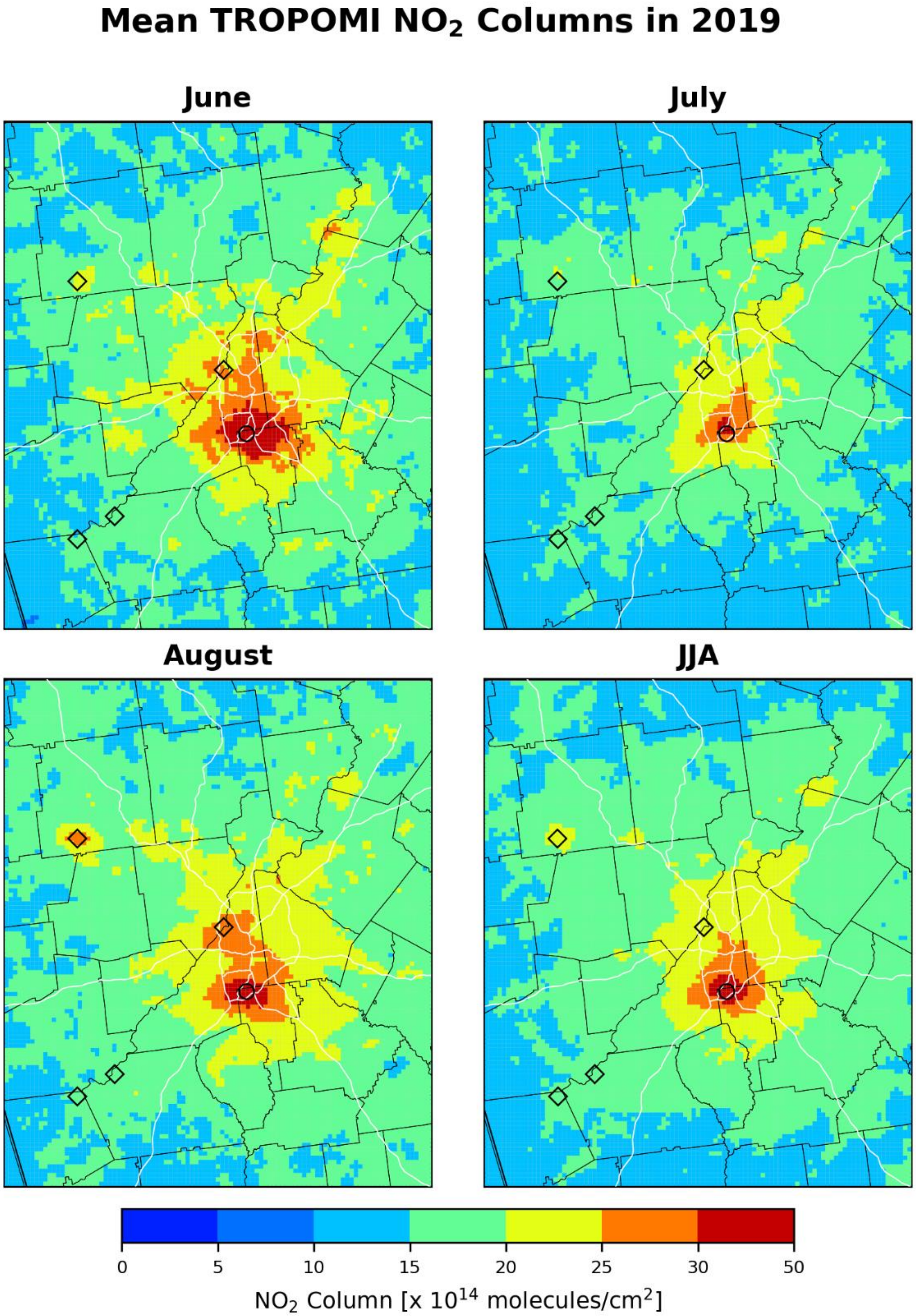

Figure B6. Mean TROPOMI Tropospheric NO_2 columns over the Metro Atlanta area in June, July, August, and June-August during 2019.

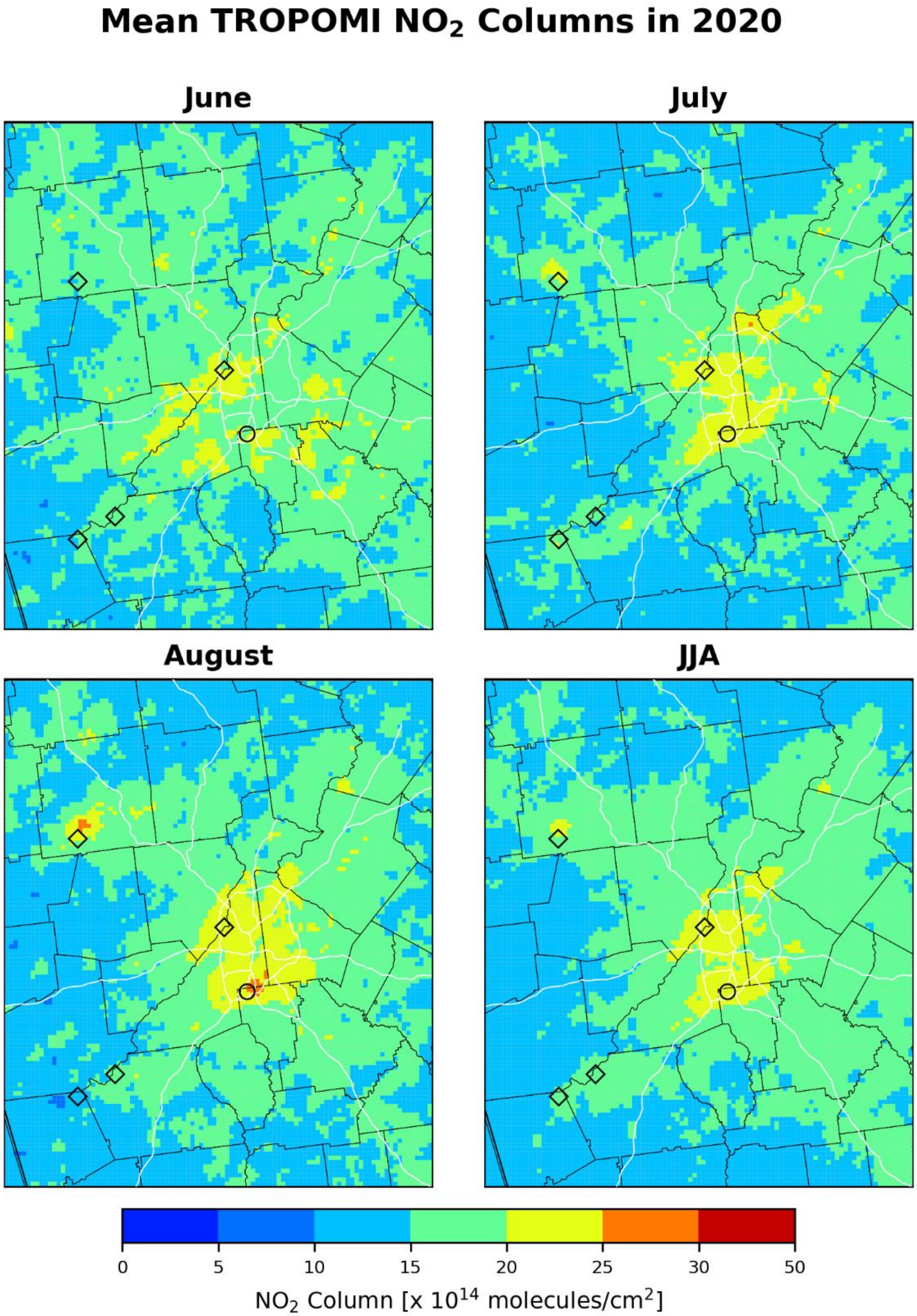

Figure B7. Mean TROPOMI Tropospheric NO_2 columns over the Metro Atlanta area in June, July, August, and June-August during 2020.

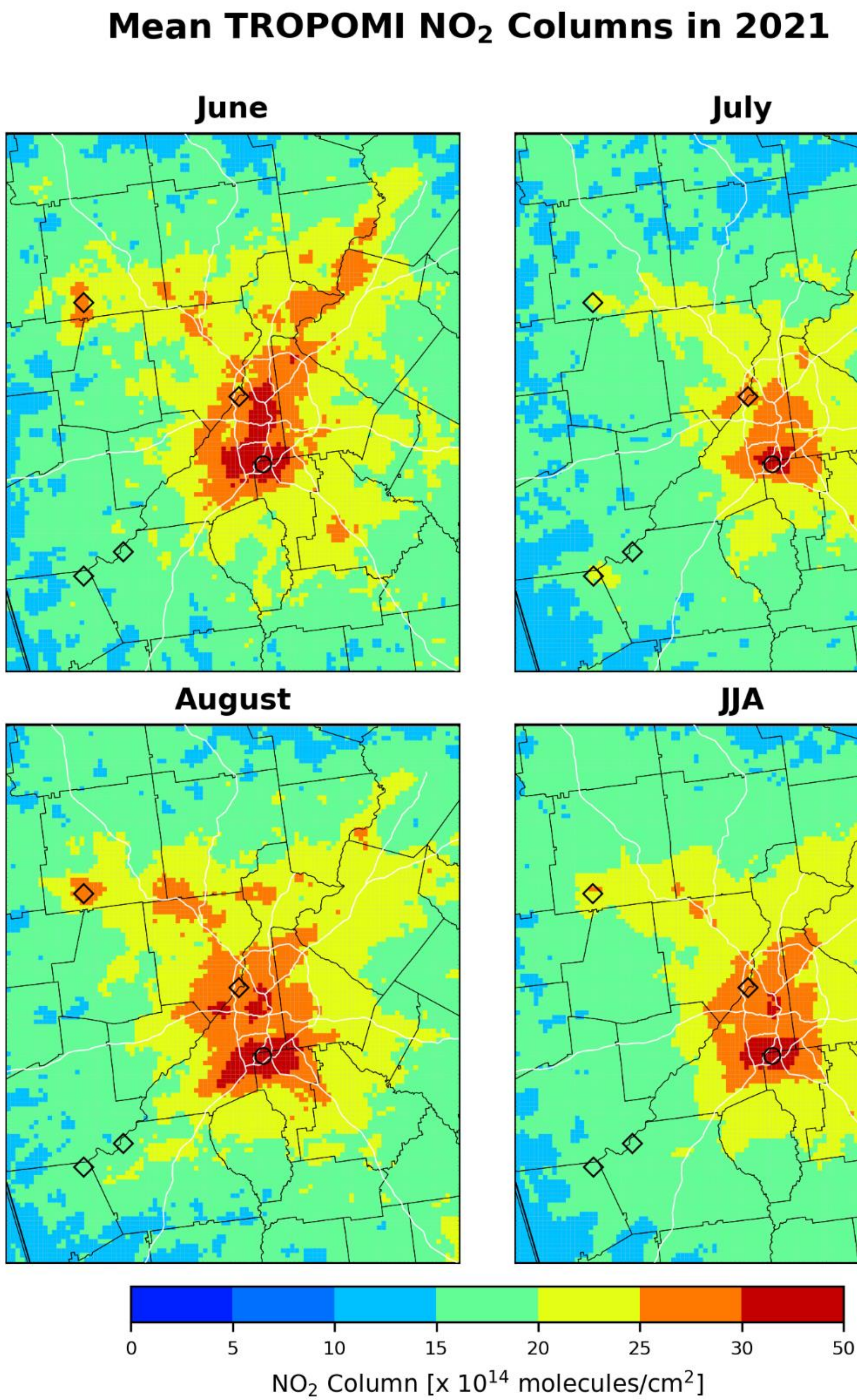

Figure B8. Mean TROPOMI Tropospheric NO_2 columns over the Metro Atlanta area in June, July, August, and June-August during 2021.

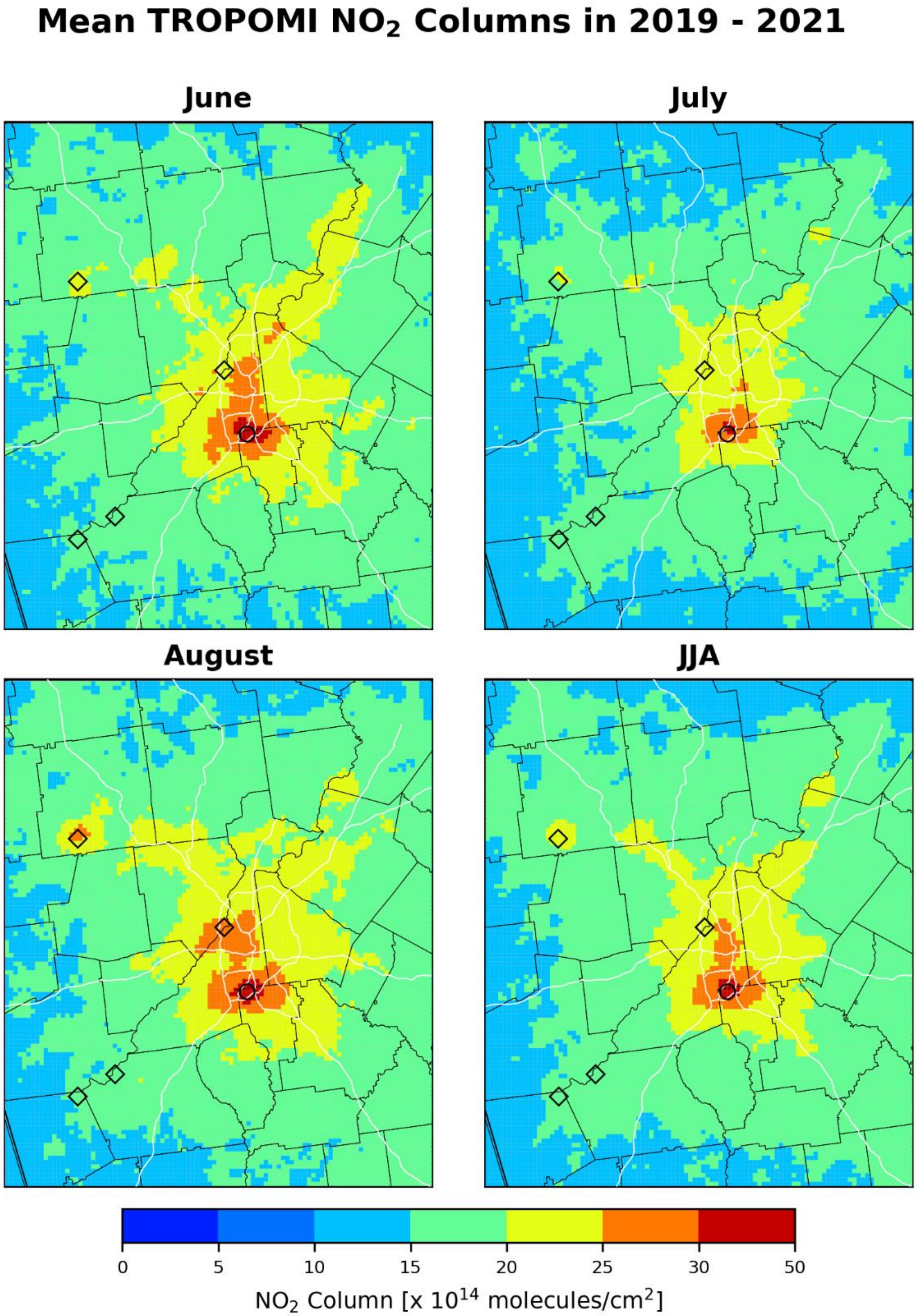

Figure B9. Mean TROPOMI Tropospheric NO_2 columns over the Metro Atlanta area in June, July, August, and June-August during 2019-2021.

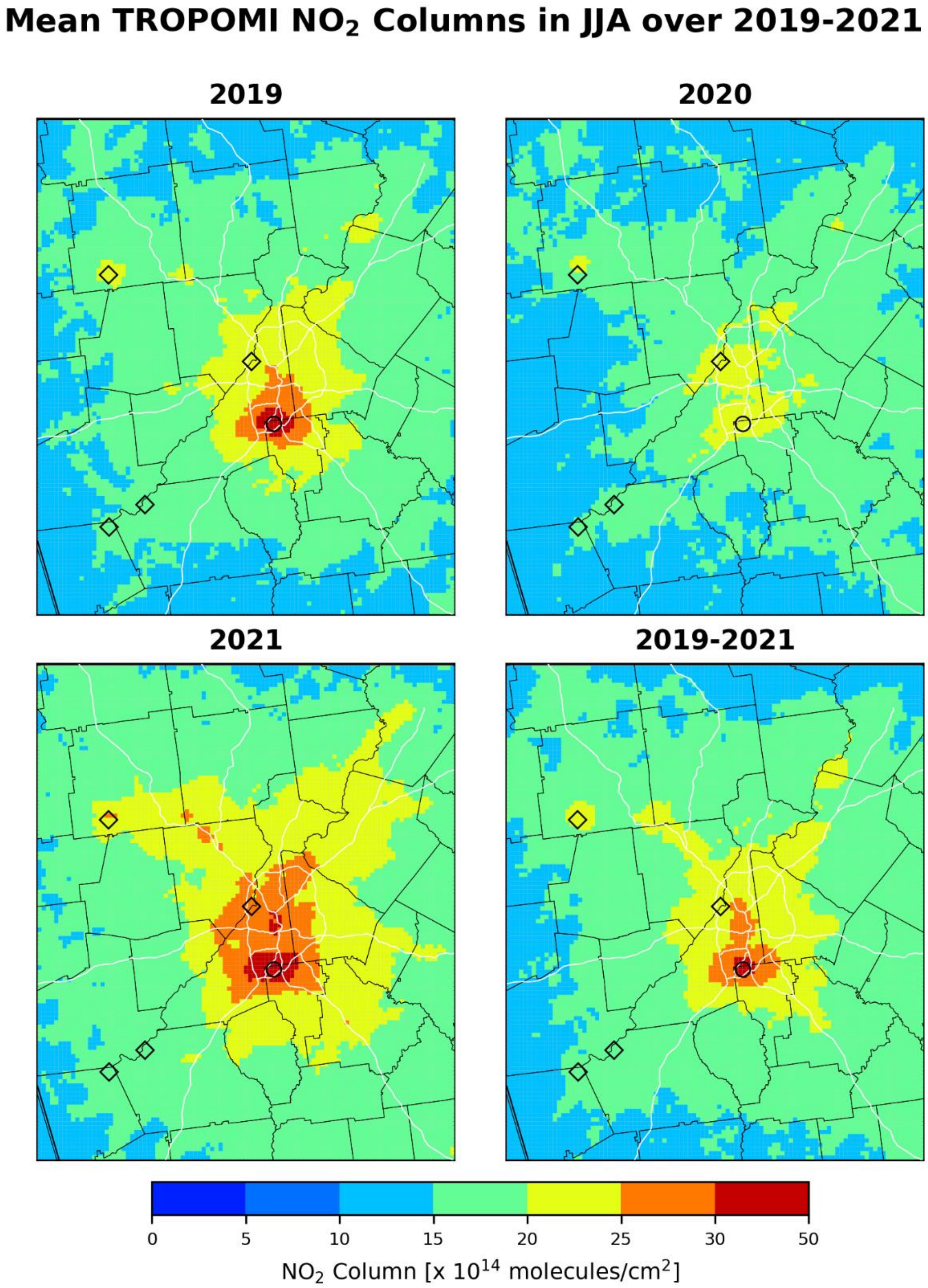

Figure B10. Mean TROPOMI Tropospheric NO_2 columns over the Metro Atlanta area in June-August during 2019, 2020, 2021, and 2019-2021.

Appendix C

TROPOMI NO_2 VCDs for days before, on, and after ozone exceedance days in 2019-2021

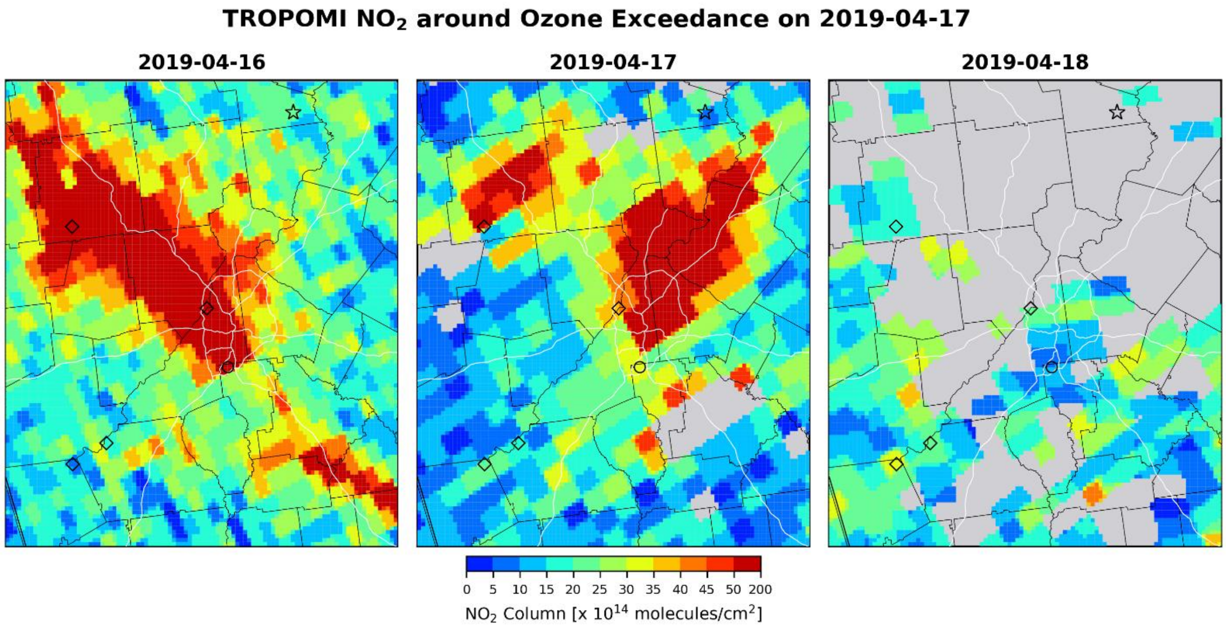

Figure C1. Daily TROPOMI NO_2 tropospheric columns over the Metro Atlanta area on April 16-17, 2019. Power plants, the Hartsfield-Jackson Atlanta International Airport, exceedance monitors are depicted as hollow diamonds, the circle, and stars.

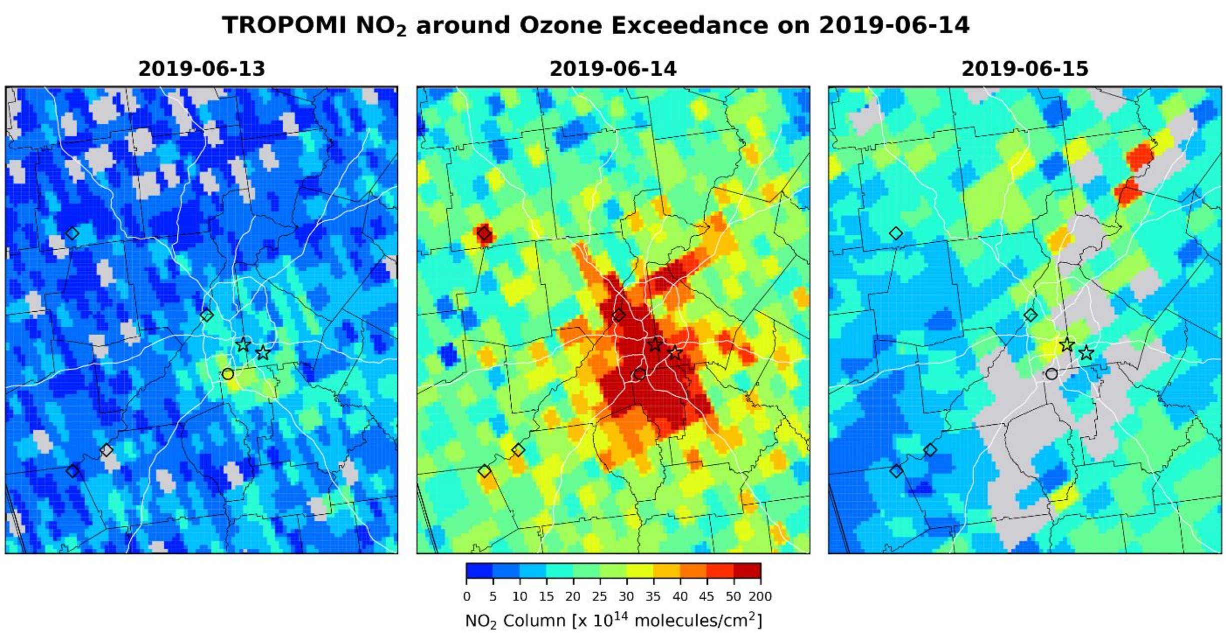

Figure C2. Daily TROPOMI NO_2 tropospheric columns over the Metro Atlanta area on June 13-15, 2019. Power plants, the Hartsfield-Jackson Atlanta International Airport, exceedance monitors are depicted as hollow diamonds, the circle, and stars.

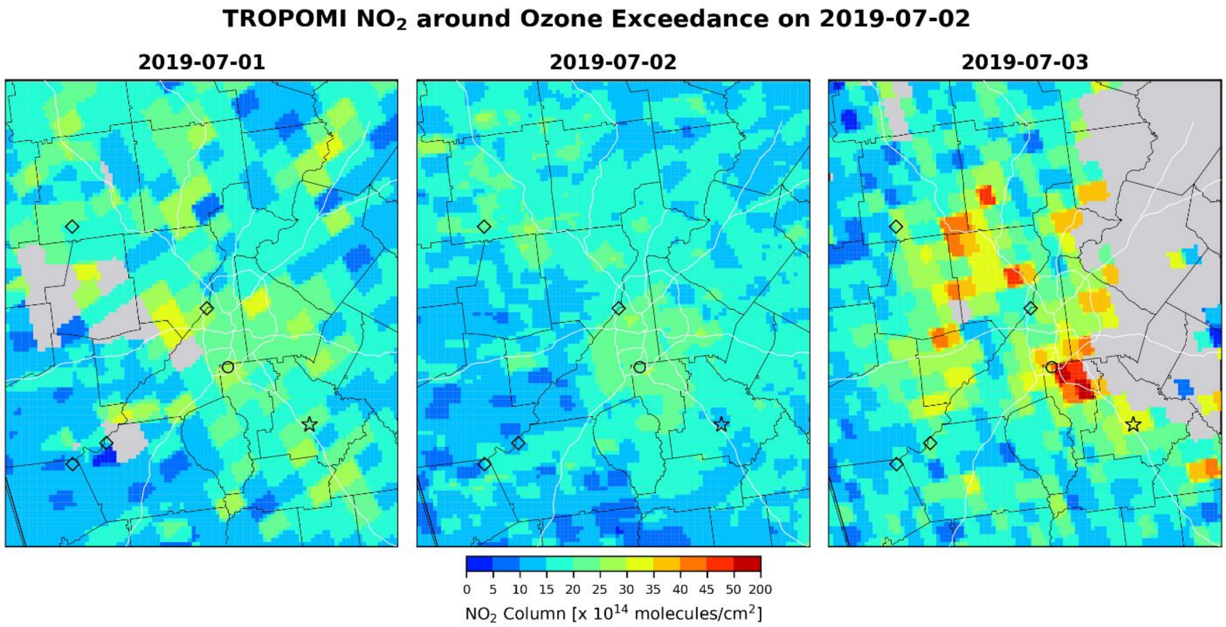

Figure C3. Daily TROPOMI NO_2 tropospheric columns over the Metro Atlanta area on July 1-3, 2019. Power plants, the Hartsfield-Jackson Atlanta International Airport, exceedance monitors are depicted as hollow diamonds, the circle, and stars.

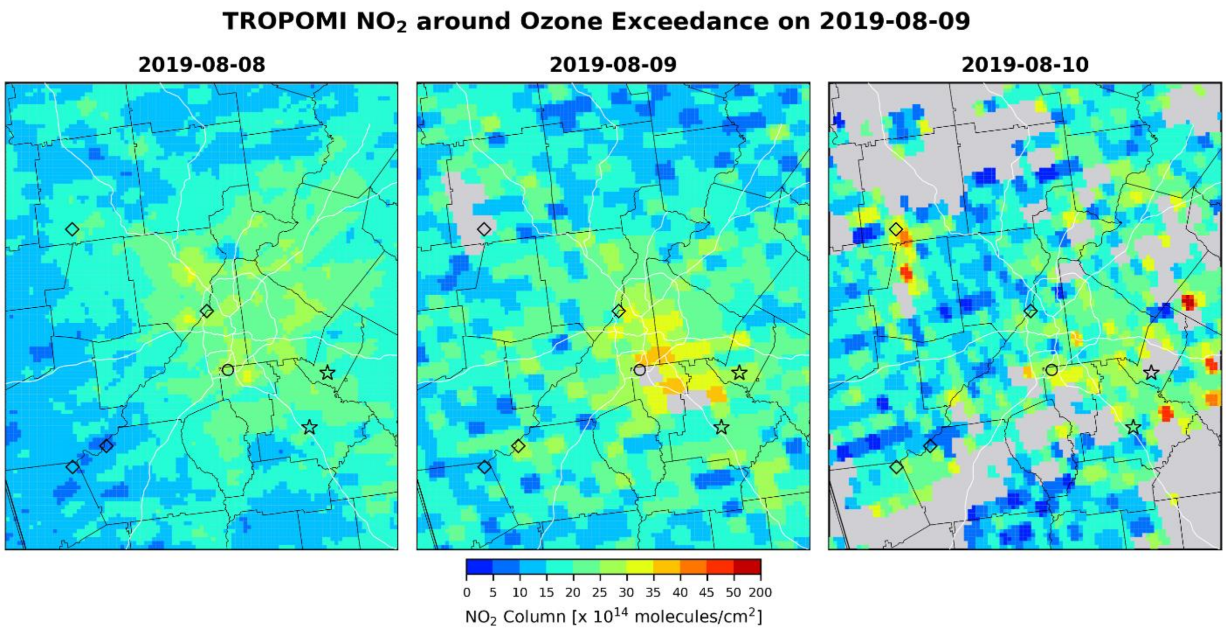

Figure C4. Daily TROPOMI NO_2 tropospheric columns over the Metro Atlanta area on August 8-10, 2019. Power plants, the Hartsfield-Jackson Atlanta International Airport, exceedance monitors are depicted as hollow diamonds, the circle, and stars.

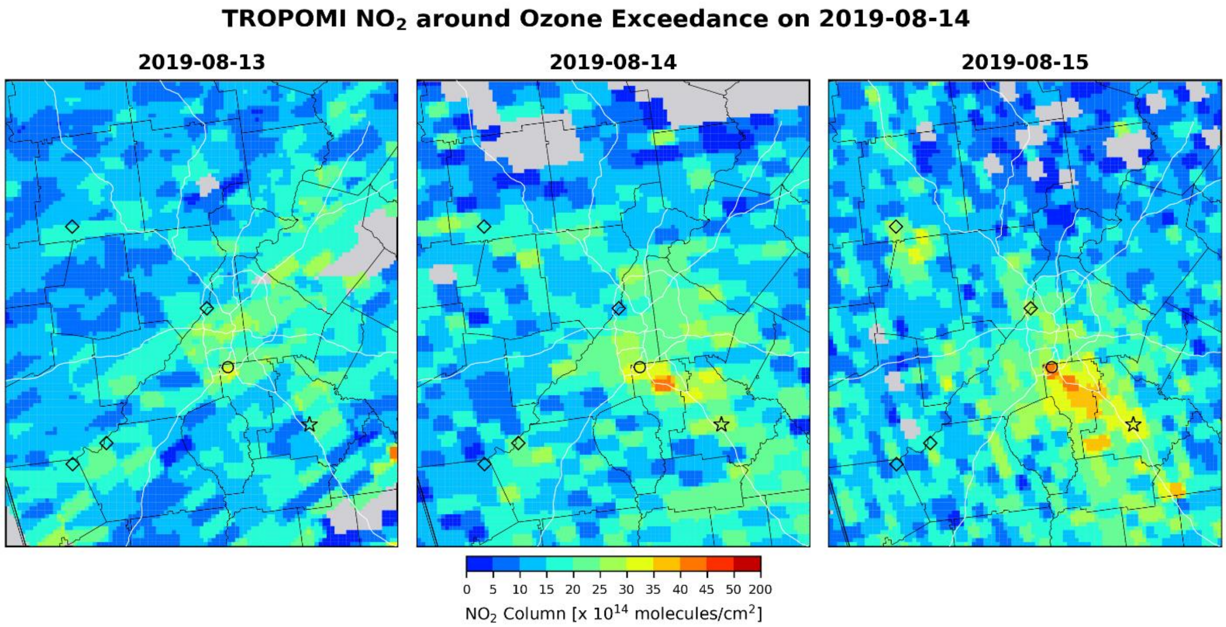

Figure C5. Daily TROPOMI NO_2 tropospheric columns over the Metro Atlanta area on August 13-15, 2019. Power plants, the Hartsfield-Jackson Atlanta International Airport, exceedance monitors are depicted as hollow diamonds, the circle, and stars.

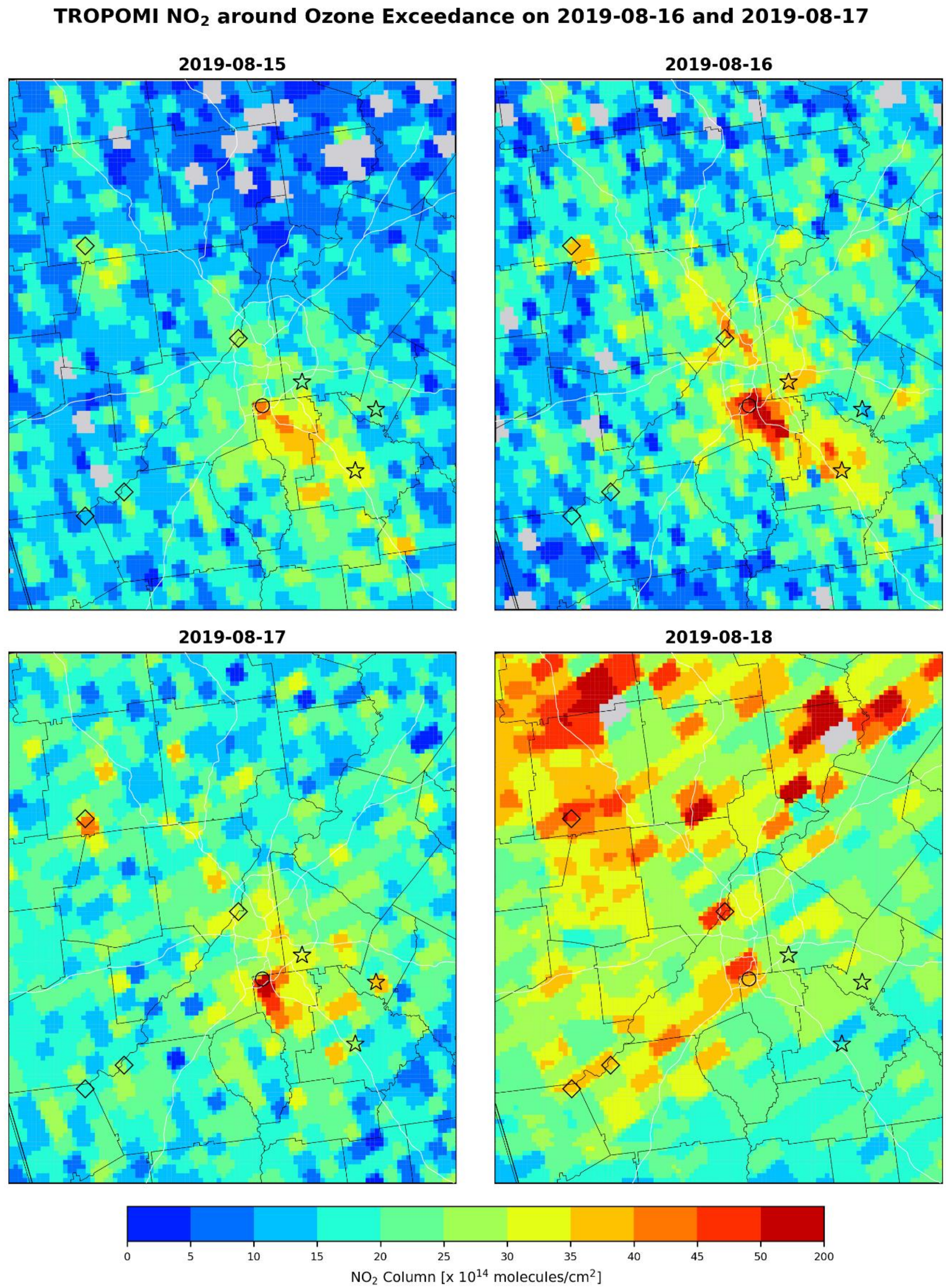

Figure C6. Daily TROPOMI NO_2 tropospheric columns over the Metro Atlanta area on August 15-18, 2019. Power plants, the Hartsfield-Jackson Atlanta International Airport, exceedance monitors are depicted as hollow diamonds, the circle, and stars.

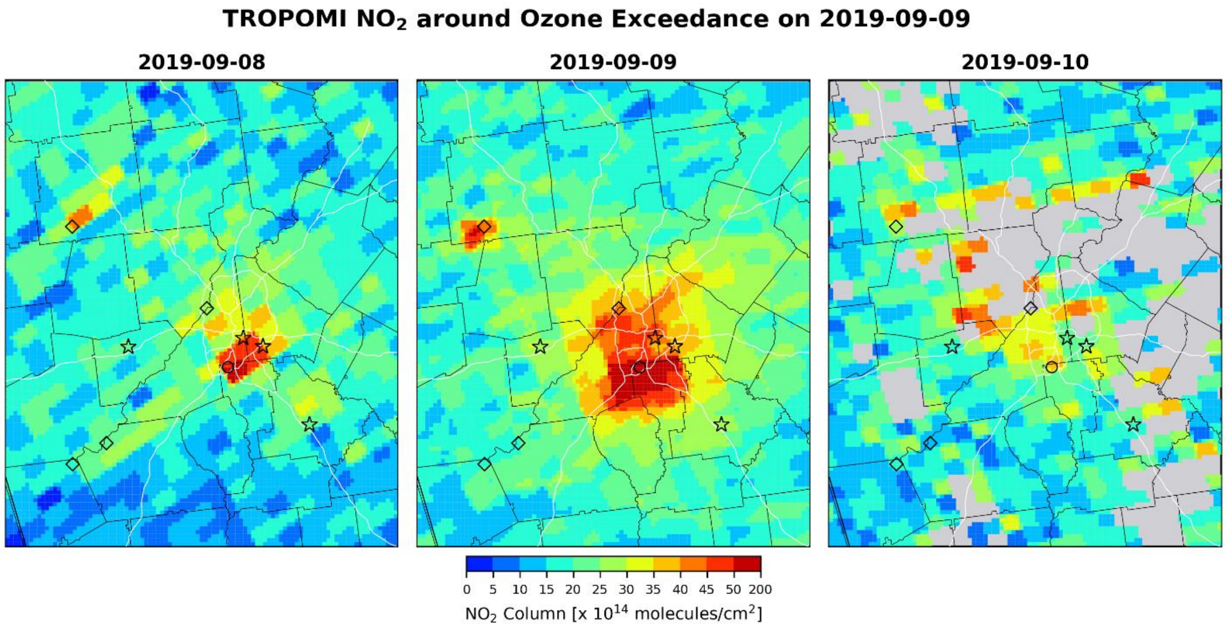

Figure C7. Daily TROPOMI NO_2 tropospheric columns over the Metro Atlanta area on September 8-10, 2019. Power plants, the Hartsfield-Jackson Atlanta International Airport, exceedance monitors are depicted as hollow diamonds, the circle, and stars.

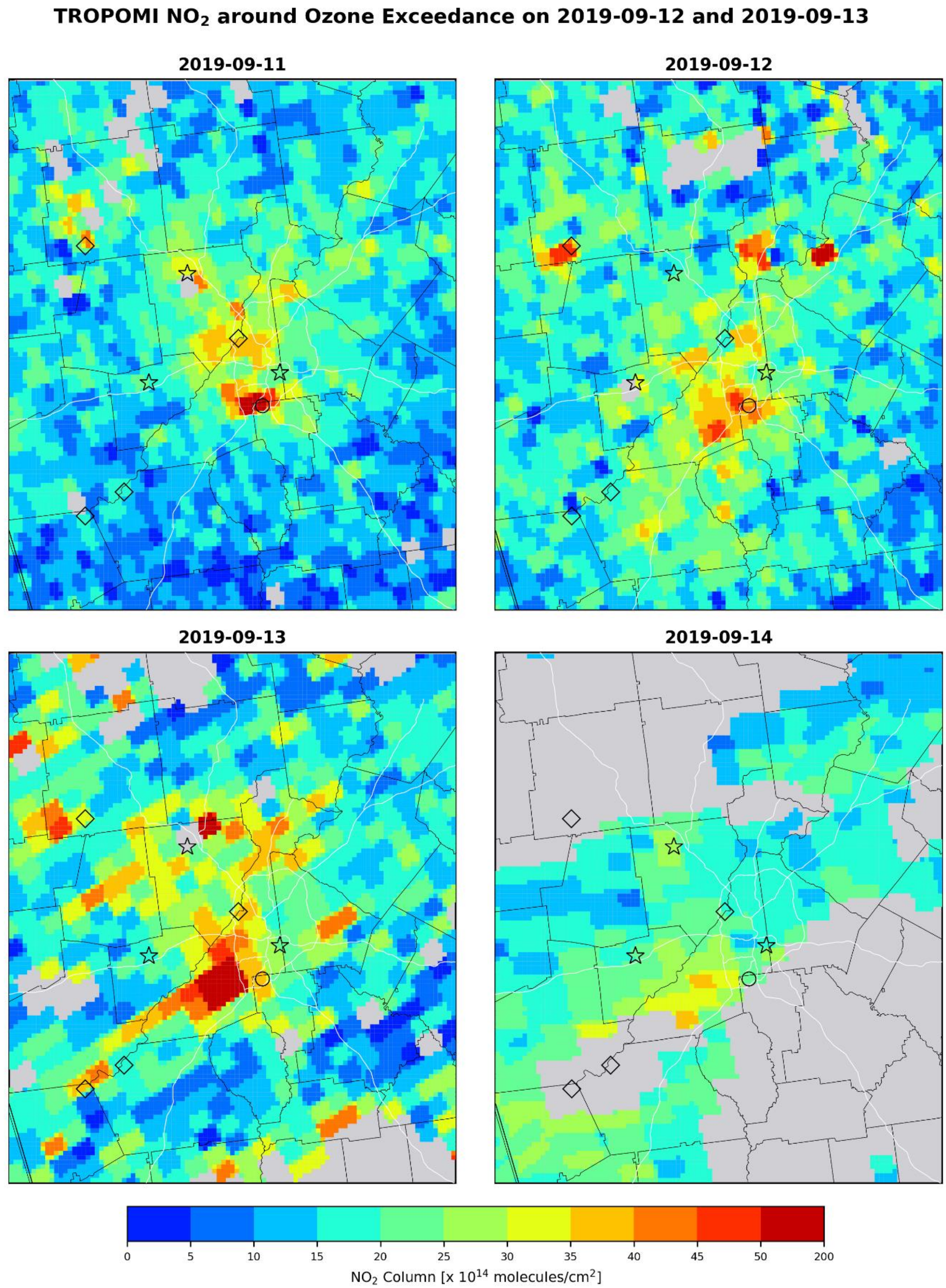

Figure C8. Daily TROPOMI NO_2 tropospheric columns over the Metro Atlanta area on September 11-14, 2019. Power plants, the Hartsfield-Jackson Atlanta International Airport, exceedance monitors are depicted as hollow diamonds, the circle, and stars.

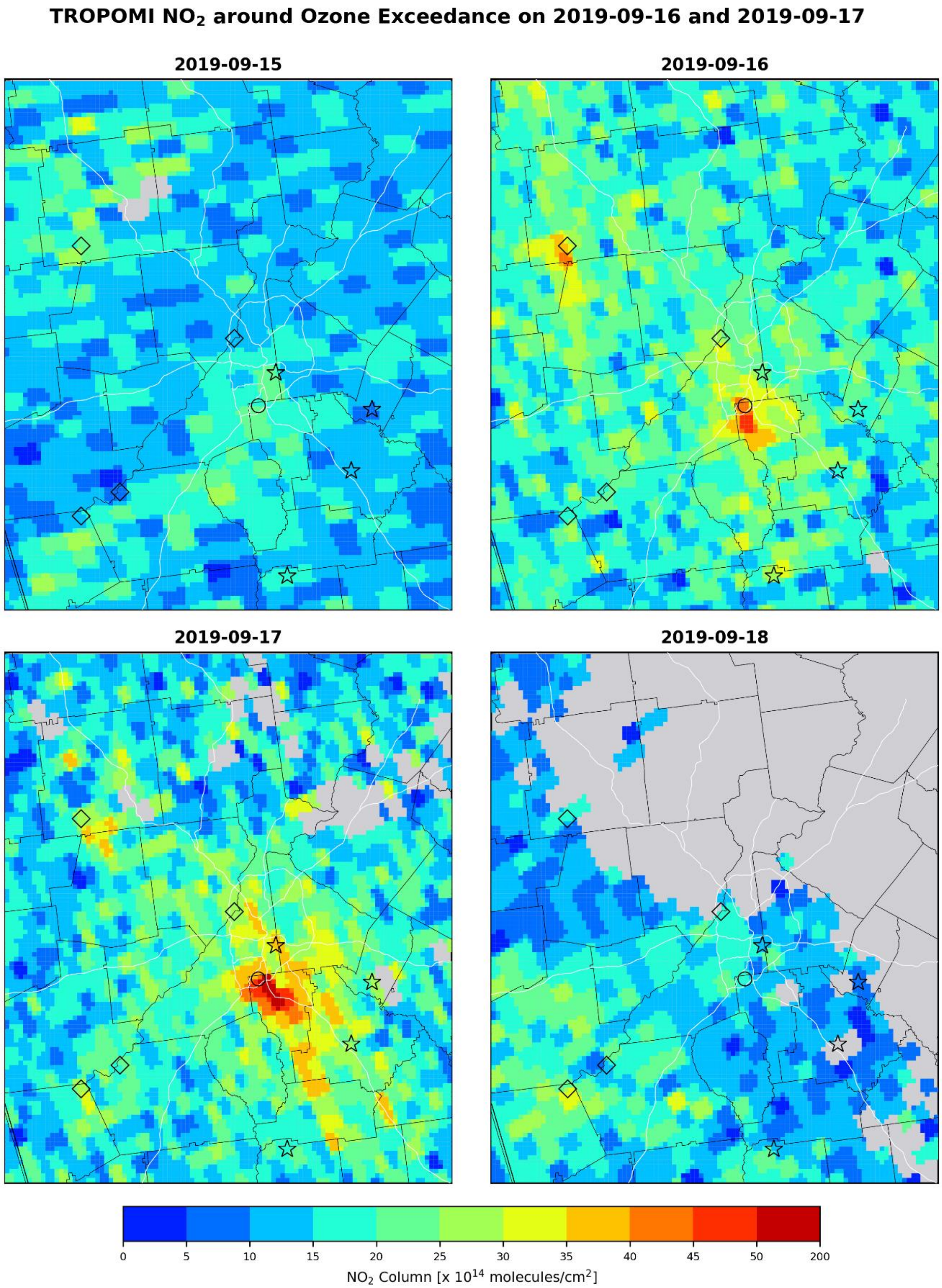

Figure C9. Daily TROPOMI NO_2 tropospheric columns over the Metro Atlanta area on September 15-18, 2019. Power plants, the Hartsfield-Jackson Atlanta International Airport, exceedance monitors are depicted as hollow diamonds, the circle, and stars.

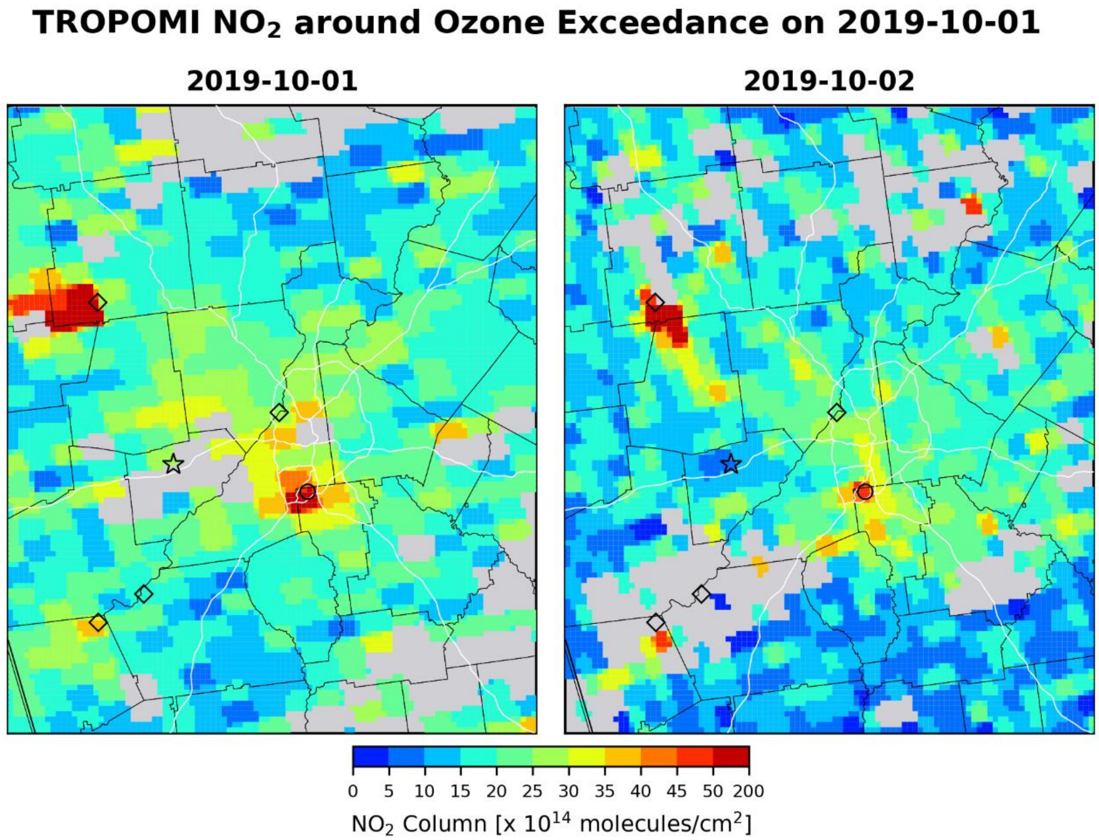

Figure C10. Daily TROPOMI NO_2 tropospheric columns over the Metro Atlanta area on October 1-2, 2019. Power plants, the Hartsfield-Jackson Atlanta International Airport, exceedance monitors are depicted as hollow diamonds, the circle, and stars. September 30, 2019 was an O_3 exceedance day. However, no TROPOMI data are available on September 29 and 30, 2019.

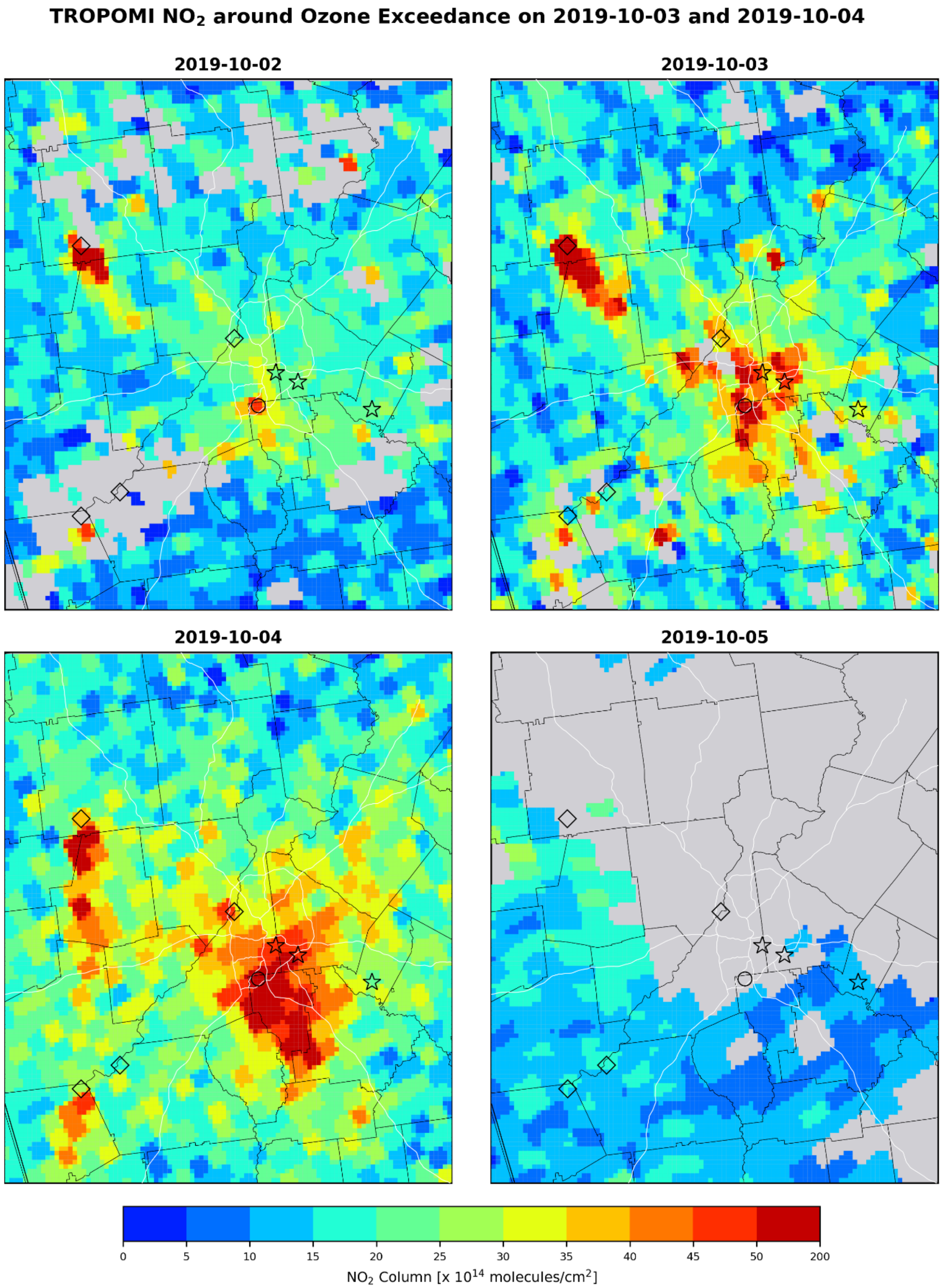

Figure C11. Daily TROPOMI NO_2 tropospheric columns over the Metro Atlanta area on October 2-4, 2019. Power plants, the Hartsfield-Jackson Atlanta International Airport, exceedance monitors are depicted as hollow diamonds, the circle, and stars.

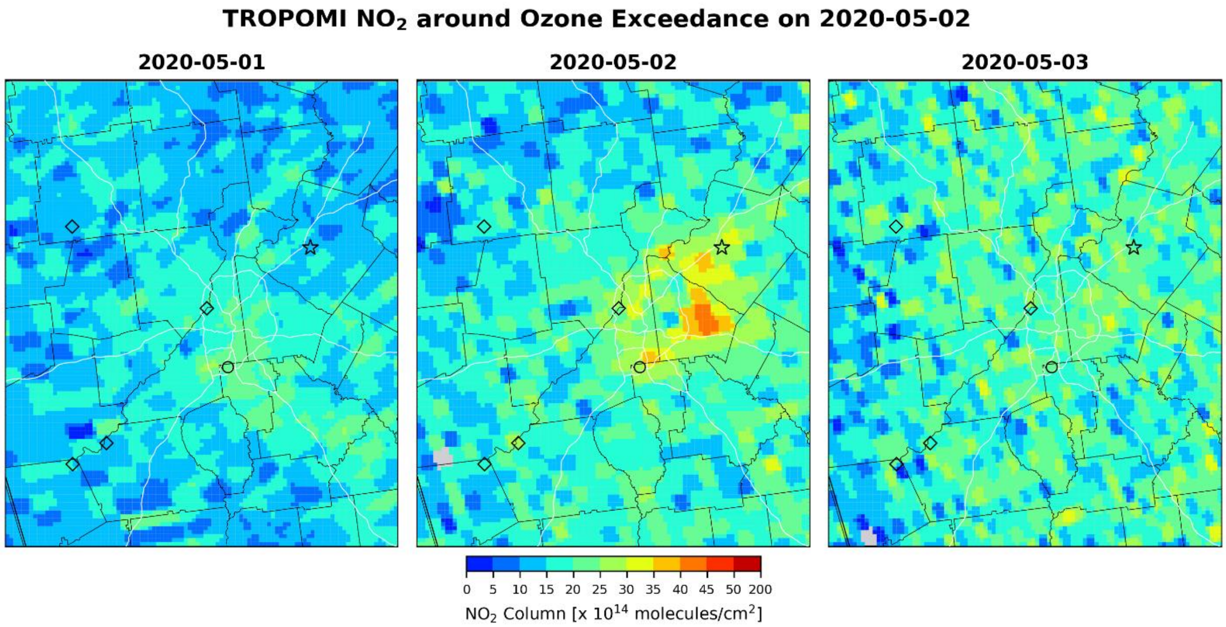

Figure C12. Daily TROPOMI NO_2 tropospheric columns over the Metro Atlanta area on May 1-3, 2020. Power plants, the Hartsfield-Jackson Atlanta International Airport, exceedance monitors are depicted as hollow diamonds, the circle, and stars.

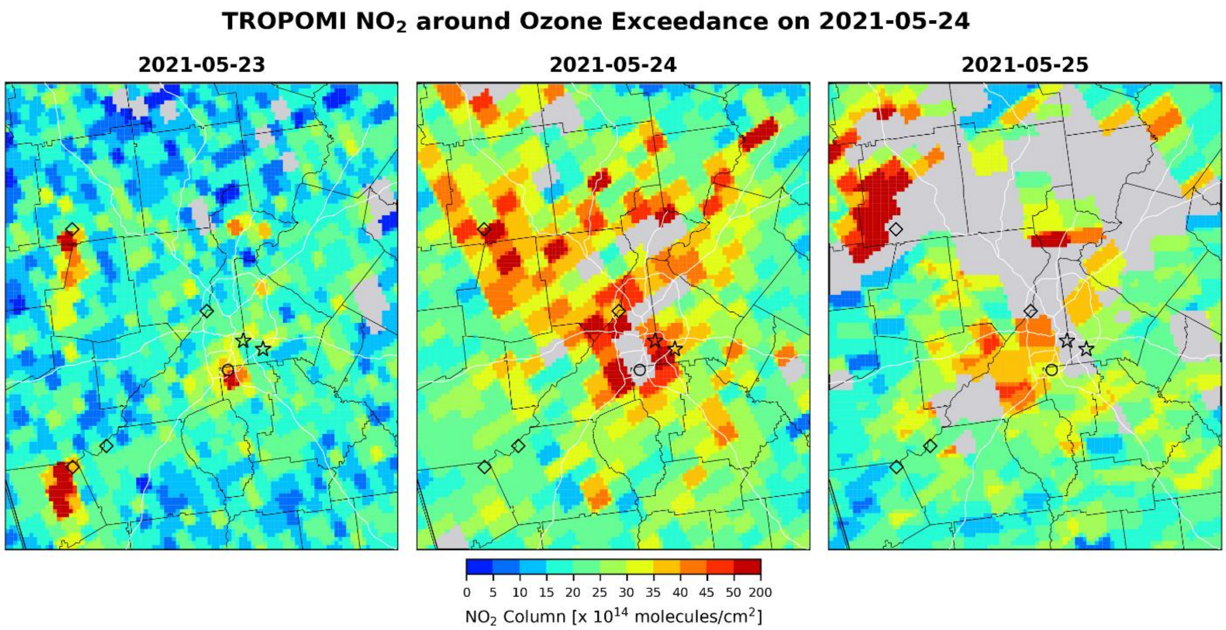

Figure C13. Daily TROPOMI NO_2 tropospheric columns over the Metro Atlanta area on May 23-25, 2021. Power plants, the Hartsfield-Jackson Atlanta International Airport, exceedance monitors are depicted as hollow diamonds, the circle, and stars.

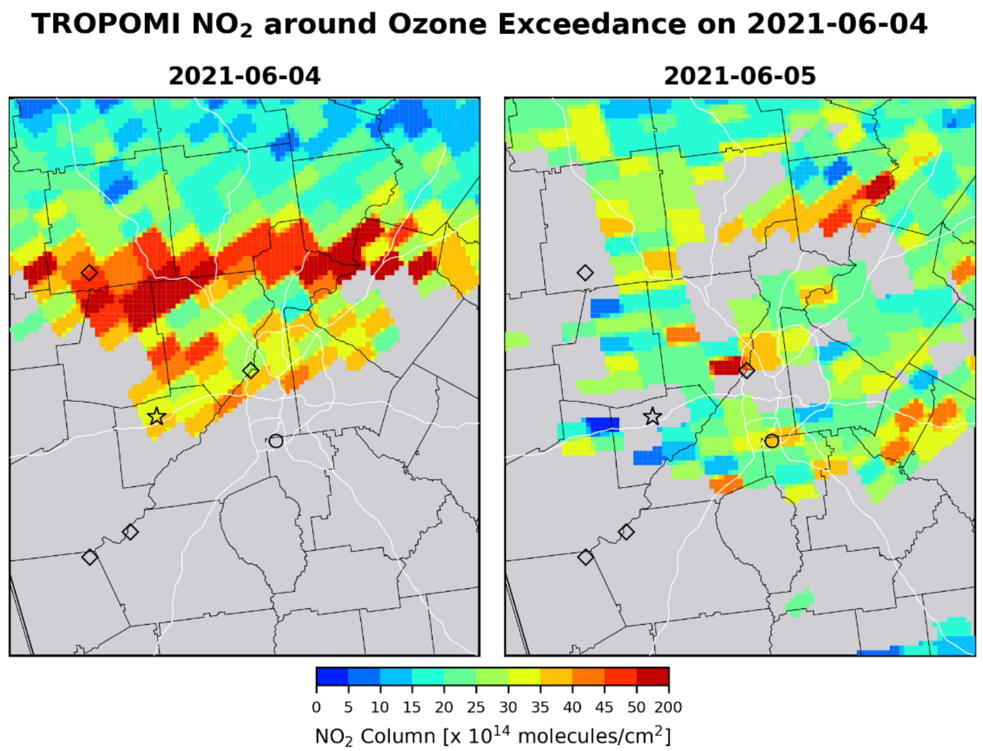

Figure C14. Daily TROPOMI NO_2 tropospheric columns over the Metro Atlanta area on June 4-5, 2021. Power plants, the Hartsfield-Jackson Atlanta International Airport, exceedance monitors are depicted as hollow diamonds, the circle, and stars. No TROPOMI data are available on June 3, 2021.

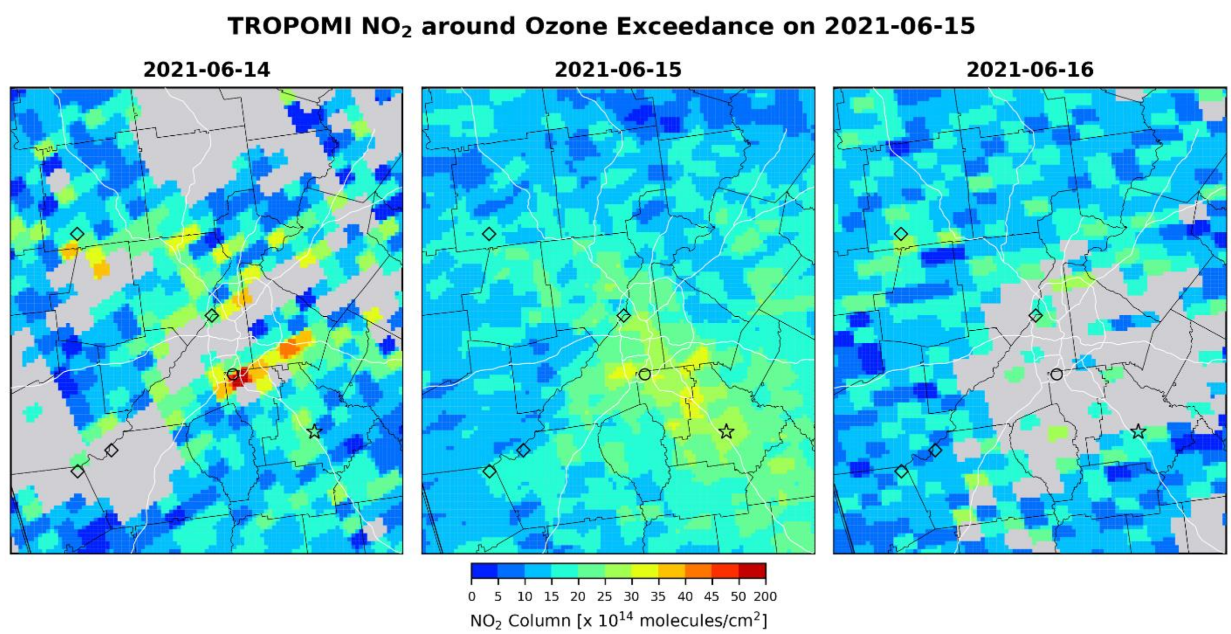

Figure C15. Daily TROPOMI NO_2 tropospheric columns over the Metro Atlanta area on June 14-16, 2021. Power plants, the Hartsfield-Jackson Atlanta International Airport, exceedance monitors are depicted as hollow diamonds, the circle, and stars.

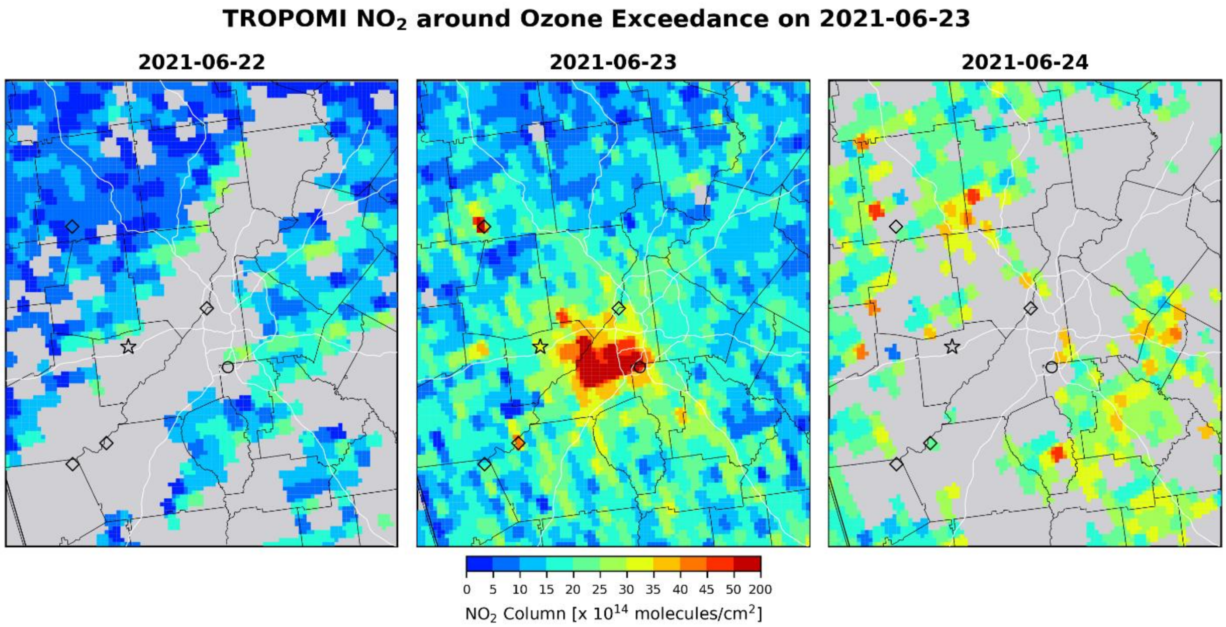

Figure C16. Daily TROPOMI NO_2 tropospheric columns over the Metro Atlanta area on June 22-24, 2021. Power plants, the Hartsfield-Jackson Atlanta International Airport, exceedance monitors are depicted as hollow diamonds, the circle, and stars.

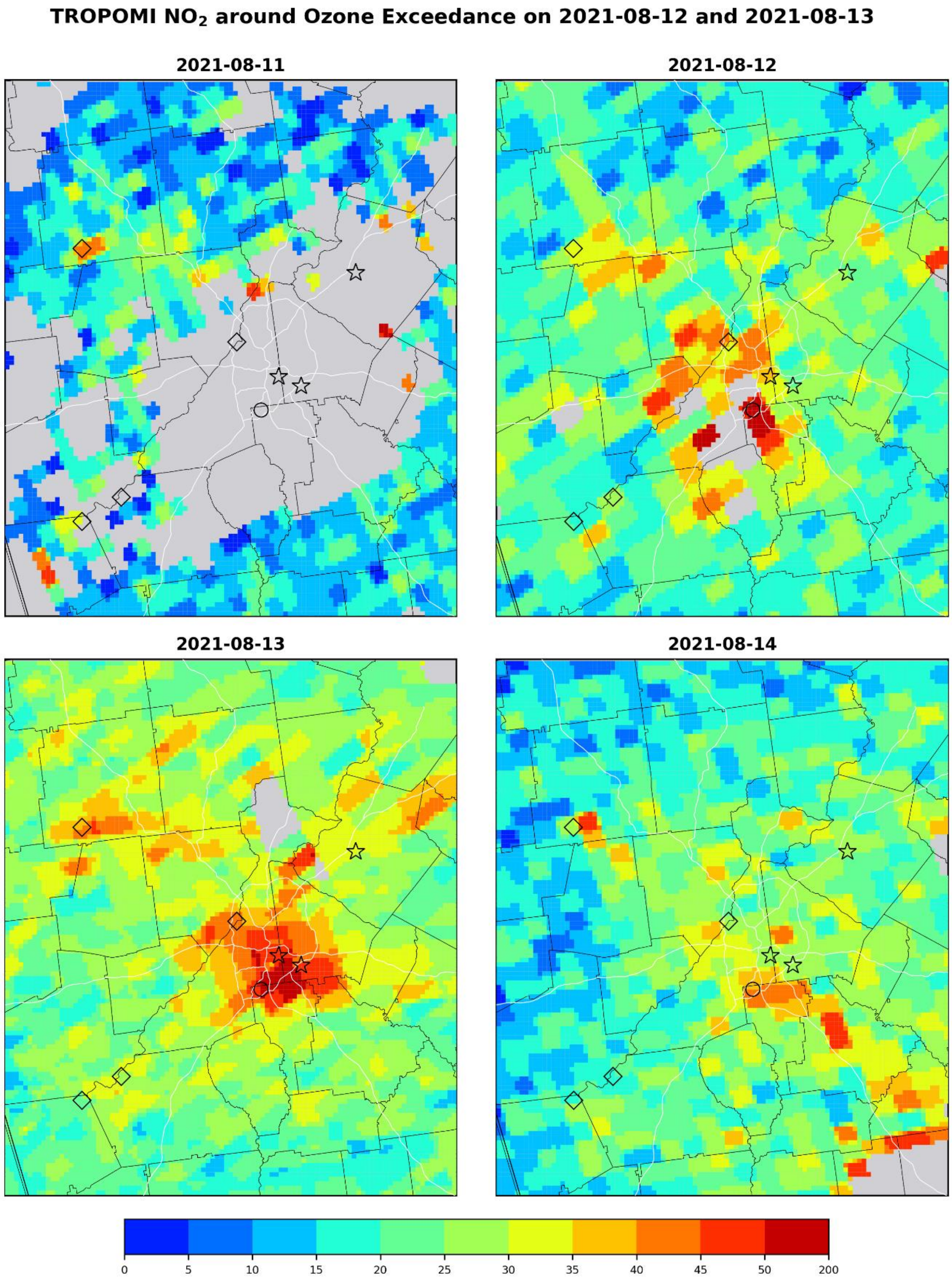

Figure C17. Daily TROPOMI NO_2 tropospheric columns over the Metro Atlanta area on August 12-14, 2021. Power plants, the Hartsfield-Jackson Atlanta International Airport, exceedance monitors are depicted as hollow diamonds, the circle, and stars.

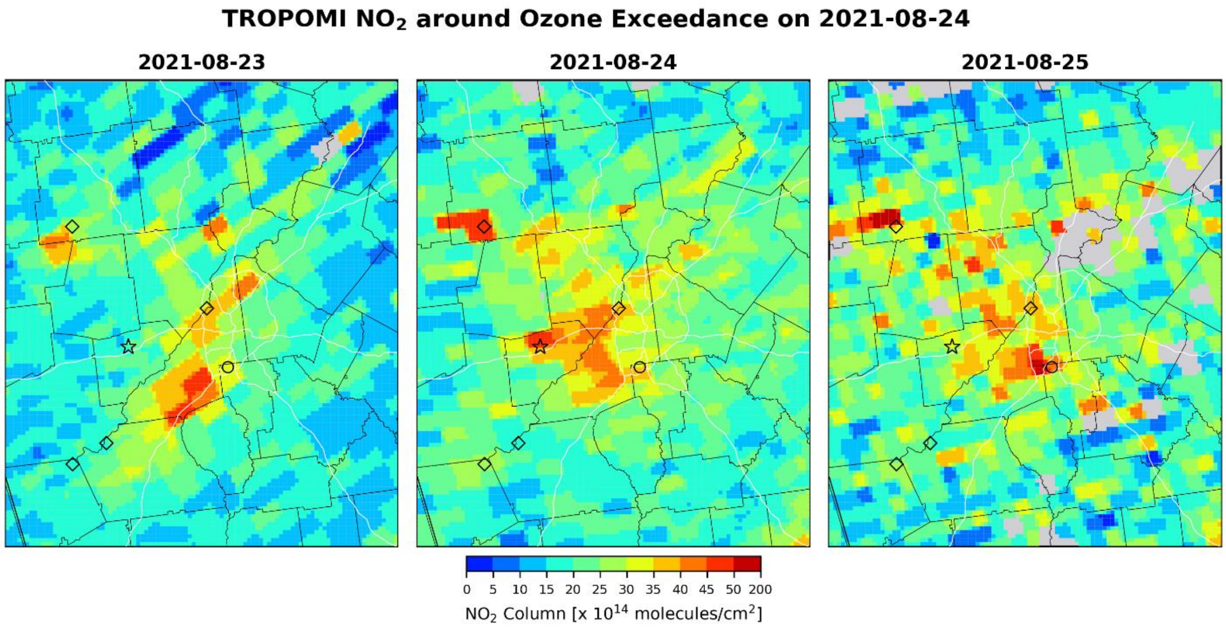

Figure C18. Daily TROPOMI NO_2 tropospheric columns over the Metro Atlanta area on August 23-25, 2021. Power plants, the Hartsfield-Jackson Atlanta International Airport, exceedance monitors are depicted as hollow diamonds, the circle, and stars.