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Spatiotemporal Trends of Ozone, Nitrogen Dioxide, and Fine Particulate Matter in North Carolina from 2010-2020

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Abstract

Pollutants in the atmosphere are known to cause negative human health effects and environmental degradation. Air pollution is linked to increased asthma, risk of lung cancer, and other cardiovascular and respiratory diseases. Three of the most important pollutants are ground-level ozone, nitrogen dioxide, and fine particulate matter. This study is investigating how levels of each of these pollutants changed in North Carolina from 2010 to 2020. Data were collected from the Environmental Protection Agency's (EPA) air quality data bank, and a trend analysis was performed to quantify statewide and regional (coastal, piedmont, and mountains) temporal changes. This research found that from 2010-2020, the average levels of all three pollutants decreased across the state. Statewide, nitrogen dioxide levels decreased by 46.3% from 49.5 parts per billion to 26.6 parts per billion using the annual 98th percentile, ozone levels decreased by 24.1% from 0.073 parts per million to 0.053 parts per million using the annual 4th highest 8-hour average, and fine particulate matter levels decreased by 36.4% from 9.97 $\mu g/m^3$ to 6.34 $\mu g/m^3$ using the average daily mean. The effects of Covid-19 and the 2016 wildfires on air pollution were researched as case studies: the wildfires caused an increase in all three pollutants, and during 2020 the concentration of all pollutants decreased.

1. Introduction

Air pollutants, specifically nitrogen dioxide (NO_2), ozone (O_3), and fine particulate matter ($PM_{2.5}$) are largely created from anthropogenic sources and cause negative health effects. NO_2 is emitted from primary sources, and when breathed in can irritate airways, aggravate respiratory diseases, and can lead to hospital admissions due to increased coughing, wheezing, and difficulty breathing.[1] Long term exposure to NO_2 can also contribute to the development of asthma and increase susceptibility to respiratory infections.[2]Ozone is a secondary pollutant and is created from precursor emissions, such as nitrogen oxides (NOx) and volatile organic compounds (VOCs).[3] Ozone can also cause increased respiratory ailments, such as coughing, sore or scratchy throats, difficulty breathing, and susceptibility to infections.[4] Children are at the greatest risk from exposure to ozone because their lungs are still developing, and they are more likely to be outdoors when ozone concentrations are highest.[5] $PM_{2.5}$, similar to NO_2 and O_3, can cause an increase in respiratory diseases, including heart and lung disease, asthma, and a decrease in lung functioning.[6] $PM_{2.5}$ has both primary and secondary sources, as it can be emitted directly from cars or power plants, or formed in the atmosphere through reactions with other compounds.[7]

In North Carolina, the main emissions sources for all three pollutants are power plants and transportation[8]. $PM_{2.5}$ can also arise from forest fires, which are a natural emissions source. Many emission sources of primary $PM_{2.5}$ and NOx are found in urban and industrial areas of the state such as at airports, foundries, food processing plants, and steel mills.[9] Cars, power plants, industrial boilers, refineries, and chemical plants can also emit ozone precursors, and the transformation from precursor to ground-level ozone is more prevalent in urban areas during summer months when there is more sunlight. Charlotte, the Triangle, Greensboro, Fayetteville, and Asheville are all areas that have high levels of ozone production.[10]

In the last few decades, emissions in North Carolina have trended downwards. The Clean Smokestacks Act of 2002 required significant emissions reductions from coal-fired power plants in North Carolina, and there have been substantial reductions of emissions from smokestacks since the act was put into place. From 1990 to 2017, statewide emissions of sulfur dioxide have declined by 91%, carbon monoxide emissions have declined by 69%, NOx emissions have declined by 63%, $PM_{2.5}$ emissions have declined by 49%, and VOC emissions have declined by 60%.[11] Mobile source emissions such as vehicle emissions have also been declining recently, which could be due in part to increased emissions standards and improved efficiency of vehicles.[12] Emissions of sulfur dioxide (a precursor to $PM_{2.5}$) and carbon monoxide (a precursor to ozone) have also seen decreases.[13] There are two major events that occurred in the last decade that also affected emissions trends in North Carolina: the wildfires in 2016, and the Covid-19 pandemic. The wildfires were a large emissions source event, while the pandemic was likely an emissions reduction event.

This research aims to provide quantitative answers to how much air pollution has changed from 2010-2020 and how the 2016 fires and 2020 pandemic shutdown influenced ambient pollution levels. Data from air quality monitors were collected and analyzed to find what changes NO_2, O_3, and $PM_{2.5}$ has undergone in the last decade. A trend analysis was completed to find patterns in air pollution concentrations throughout the decade, as well as outlying spikes and drops in concentrations. Analyses of air pollution concentrations were also completed on the regional scale, looking at the differences in patterns between the Mountain, Piedmont, and Coastal regions of the state.

2. Methods

This research collected data from all regulatory NO_2, O_3, and $PM_{2.5}$ monitors in North Carolina (Table 1). These data were found in the EPA Outdoor Air Quality monitor values reports database[14]. Data were taken from the years 2010 to 2020. Data were collected for all monitors for every year they were available – some monitors were inactive during certain periods, so did not contain the full dataset, but they were still included in the analysis. If a monitor had fewer than 15 days of measurements in a given year it was not included in the analysis, as it did not contain a sufficient account of that area's pollutant concentrations. For all monitors and pollutants, the daily value recorded by each monitor is as follows: for NO_2 this was the maximum 1-hr average daily value in parts per billion (ppb), for O_3 this was the maximum 8-hr average value in parts per million (ppm), and for $PM_{2.5}$ this was the maximum 1-hr average concentration in $\mu g/m^3$. Data were also collected to calculate the design values for each pollutant: for NO_2 this was the annual 98th percentile of daily 1-hr maxima in ppb, for O_3 this was the annual fourth highest 8-hr daily maximum value in ppm, and for $PM_{2.5}$ this was the annual mean of 1-hr daily averages value in $\mu g/m^3$. A design value is a statistic that describes the air quality status of a given location relative to the level of the National Ambient Air Quality Standards.[15] Relevant metrics for design value calculations were obtained from the EPA's summary Monitor Value Reports.[16]

2.1. Design Values

A design value is calculated to see if a monitor is within attainment of the National Ambient Air Quality Standards (NAAQS) – all monitors' design values must be within attainment of the NAAQS for the state to be within attainment. To calculate design values, a three-year running average must be taken for each pollutant. The design value was calculated for each individual monitor.

For NO_2, a concentration reading is taken every hour at each monitoring site. The largest hourly concentrations reading for each day is then compiled in a list, and the value that fall on the 98th percentile for the entire year is used. This value is then averaged with the 98th percentile values from the previous two years using a running three-year average, which creates the design value. For example, if one were calculating the design value for 2020, one would use the 98th percentile values from 2020, 2019, and 2018. Equation 1 below shows this calculation, where DV is Design Value, M_y is the metric for the first year (in this example, 2020), M_{y-1} is the metric for the year before the first year (in this example, 2019), and M_{y-2} is the metric two years before the first year (in this example, 2018). The current primary standard provided by the NAAQS for NO_2 is 100ppb.

$$DV = \frac{M_y - M_{y-1} - M_{y-2}}{3} \quad (1)$$

To calculate the design value for O_3, a three-year running average of the annual 4th highest daily 8-hour average is taken. To find this value, each day is broken up into running 8-hour periods. The first time frame would be taken, for example, from 12am to 8am, the second from 1am to 9am, and so on. Of those 8-hour averaging periods, the highest daily concentration is taken each day. Of all the daily highest values, the 4th highest for the year is used to calculate the design value. For example, if you were to calculate the design value for 2020, you would use the 4th-highest daily maximum 8-hour concentration from the years 2020, 2019, and 2018 averaged together (Equation 1). The current primary and secondary standard provided by the NAAQS for O_3 is 0.070 ppm.

To calculate the design value for $PM_{2.5}$, a three-year running average of the annual daily mean 1-hr value is used. To find this value, a concentration reading is taken every hour at each monitoring location. From all of these hourly values, the yearly mean is calculated. This value is then averaged with the yearly mean from the previous two years to calculate the design value. For example, to find the design value for 2020, you would average the annual mean values for 2020, 2019, and 2018. The current primary standard provided by the NAAQS for $PM_{2.5}$ is 12 $\mu g/m^3$.

Some $PM_{2.5}$ monitoring sites contained multiple POCs: a POC, or parameter occurrence code, is a number that distinguishes between multiple monitors for the same pollutant at a particular monitoring site. POCs record concentrations at different intervals from each other to create a more complete database. Some POCs record concentrations every single day, every three days, or every five days. For monitoring sites that had multiple POCs that shared data collecting days, the values for each of those days were averaged, and that average was used as the value for that monitoring site for that day. This research did not differentiate between different POCs, but rather analyzed the full database of $PM_{2.5}$ measurements and combined all POCs at a monitoring site into one record.

Table 1: All Monitors in North Carolina with Years Active and County, Regionally

Region	Monitor ID Nu	Pollutant	O_3 Years Active	$PM_{2.5}$ Years Active	NO_2 Years Active	County
Mountains	370110002	O_3, $PM_{2.5}$	2010-2020	2010-2020		Avery
	370119991	O_3	2010-2020			Avery
	370210030	O_3	2010-2020			Buncombe
	370210034	$PM_{2.5}$		2010-2020		Buncombe
	370270003	O_3	2010-2020			Caldwell
	370750001	O_3	2010-2020			Graham
	370870012	$PM_{2.5}$		2010-2015		Haywood
	370870035	$PM_{2.5}$		2010-2020		Haywood
	370990005	O_3	2010-2018			Jackson
	370990006	$PM_{2.5}$		2010-2020		Jackson
	371110004	$PM_{2.5}$		2010-2014		McDowell
	371139991	O_3	2010-2020			Macon
	371210001	$PM_{2.5}$		2010-2013		Mitchell
	371210004	$PM_{2.5}$		2014-2020		Mitchell
	371730002	O_3, $PM_{2.5}$	2010-2020	2010-2020		Swain
	371730007	O_3	2012-2020			Swain
	371990004	O_3	2010-2020			Yancey

Region	Monitor ID	Pollutant	O_3 Years Active	$PM_{2.5}$ Years Active	NO_2 Years Active	County
Piedmont	370010002	$PM_{2.5}$		2010-2015		Alamance
	370030004	O_3	2010-2013			Alexander
	370030005	O_3	2013-2020			Alexander
	370330001	O_3, $PM_{2.5}$	2010-2020	2010-2016		Caswell
	370350004	$PM_{2.5}$		2010-2020		Catawba
	370370004	O_3, $PM_{2.5}$	2010-2015	2010-2014		Chatham
	370570002	$PM_{2.5}$		2010-2020		Davidson
	370590003	O_3	2010-2014			Davie
	370630015	O_3, $PM_{2.5}$	2010-2020	2010-2020		Durham
	370670022	O_3, $PM_{2.5}$, NO_2	2010-2020	2010-2020	2010-2020	Forsyth
	370670028	O_3	2010-2015			Forsyth
	370670030	O_3, $PM_{2.5}$	2010-2020	2010-2020		Forsyth
	370671008	O_3	2010-2020			Forsyth
	370690001	O_3	2010-2016			Franklin
	370710016	$PM_{2.5}$	2010-2015	2010-2015		Gaston
	370770001	O_3	2010-2020			Granville
	370810013	O_3, $PM_{2.5}$	2010-2020	2010-2020		Guilford
	370810014	$PM_{2.5}$	2010-2014	2010-2014		Guilford
	371050002	O_3, $PM_{2.5}$, NO_2	2013-2018	2014-2018	2015-2020	Lee
	371090004	O_3	2010-2020			Lincoln
	371190041	O_3, NO_2	2010-2020		2010-2020	Mecklenburg
	371190042	$PM_{2.5}$		2010-2019		Mecklenburg
	371190043	$PM_{2.5}$		2010-2016		Mecklenburg
	371190045	$PM_{2.5}$, NO_2		2017-2020	2014-2020	Mecklenburg
	371190046	O_3	2016-2020			Mecklenburg
	371190048	$PM_{2.5}$		2020		Mecklenburg
	371191005	O_3	2010-2014			Mecklenburg
	371191009	O_3	2010-2015			Mecklenburg
	371230001	$PM_{2.5}$		2010-2020		Montgomery
	371239991	O_3	2010-2020			Montgomery
	371590021	O_3, $PM_{2.5}$, NO_2	2010-2020		2020	Rowan
	371590022	O_3	2010-2013			Rowan
	371790003	O_3	2010-2020			Union
	371830014	$PM_{2.5}$, NO_2		2012-2014, 2018-202(	2014-2020	Wake
	371830020	$PM_{2.5}$		2010-2013		Wake
	371830021	$PM_{2.5}$, NO_2		2017-2020	2014-2020	Wake

Region	Monitor ID	Pollutant	O_3 Years Active	$PM_{2.5}$ Years Active	NO_2 Years Active	County
Coastal	370319991	O_3	2010-2020			Carteret
	370510009	$PM_{2.5}$		2010-2020		Cumberland
	370610002	$PM_{2.5}$		2010-2015		Duplin
	370650004	$PM_{2.5}$		2010-2013		Edgecombe
	370650099	O_3, $PM_{2.5}$	2010-2020	2011-2020		Edgecombe
	370959000	$PM_{2.5}$		2010-2020		Hyde
	371010002	O_3, $PM_{2.5}$	2010-2020	2010-2020		Johnston
	371070004	O_3, $PM_{2.5}$	2010-2020	2010-2013		Lenoir
	371170001	O_3, $PM_{2.5}$	2010-2020	2010-2015		Martin
	371290002	O_3, $PM_{2.5}$	2010-2020	2010-2020		New Hanover
	371310003	$PM_{2.5}$, NO_2		2019-2020	2019-2020	Northampton
	371470006	O_3, $PM_{2.5}$	2010-2020	2010-2020		Pitt
	371550005	$PM_{2.5}$		2010-2014		Robeson
	371910005	$PM_{2.5}$		2010-2015		Wayne

2.2. Calculating results

The overall percent change in each pollutant was calculated as a statewide average and as regional averages. The state was split into three regions (Mountain, Piedmont, and Coastal), and the values obtained for each individual monitor for each pollutant were averaged together based on regional placement. The regional averages for each pollutant were then averaged together to find a statewide average. This process was completed only for O_3 and $PM_{2.5}$, as NO_2 did not have enough monitors to complete regional analyses.

To calculate the changes in the average statewide and regional design values, a regression line was created for each pollutant. The slope of each regression line was then calculated for each monitor. Next, the slopes were grouped together by region. All the slopes for each region were averaged together to find one mean trend line slope value for each region. Then the trend line slopes for all monitors were averaged together to find the state-wide average trend line slope. These calculations were done for the time ranges 2010-2019 and 2010-2020. Calculating for these two time frames (2010-2020 and 2010-2019) was done to see if there was any change as a result of the Covid-19 pandemic lockdown in 2020. By staying at home, people were less likely to drive, which could have caused a decrease in primary emissions of these pollutants.

3. Discussion

3.1. Nitrogen Dioxide

The first pollutant analyzed was nitrogen dioxide (NO_2). Figure 1 shows the values of the 98th percentile 1-hour daily maximum values for all monitors in North Carolina from 2010-2020. Over the eleven years, NO_2 shows a steady decrease in the 98th percentile values, starting with an average for all monitors of 49.5 ppb in 2010, with the largest individual value 50 ppb (Monitor 371190041, Mecklenburg) and the lowest individual value 49 ppb (Monitor 370670022, Forsyth), and ending with an average for all monitors of 26.6 ppb in 2020, with the largest individual value 32 ppb (371190045, Mecklenburg) and the lowest individual value 12 ppb (371310003, Lee). This overall decrease of ppb in NO_2 concentrations also leads to a decrease in the design value, as that value is calculated from a three-year running average of annual values. The design value could only be calculated for the years 2012-2020, as data would have had to be collected for the years 2009 and 2008 to create design values for 2010 and 2011. The statewide average in 2012 was 45 ppb, and the statewide average in 2020 was 29.1 ppb. The current standard for ambient concentrations of NO_2 as provided by the NAAQS is 100 ppb, so all monitors met the standard. Not all monitors in North Carolina were used to calculate an individual design value – monitor 371310003 (Northampton) only collected data from 2019-2020, so did not have enough data to create a three-year running average.

Two monitors that have consistently lower concentrations than the rest were 371050002 (Lee) and 371310003 (Northampton). Monitor 371050002 (Lee) collected data from 2015-2018, and monitor 371310003 (Northampton) collected data from 2019-2020, and both had consistently lower concentration readings than the rest of the monitors. While most of the monitors lay in the 30-45 ppb range, these two monitors stayed under 15 ppb. These monitors could have lower concentration readings because they are not located close to a large city – in fact, monitor 371310003 (Northampton) is located at a high school surrounded by agricultural land and a solar farm. Most of the NO_2 monitors are located in urban areas, and so are likely to have higher concentrations due to larger amounts of vehicles and other emissions sources.

Regionally, NO_2 was not analyzed because the Mountains region of North Carolina did not have any NO_2 monitors, and the only monitor in the Coastal region is 371310003 (Northampton).

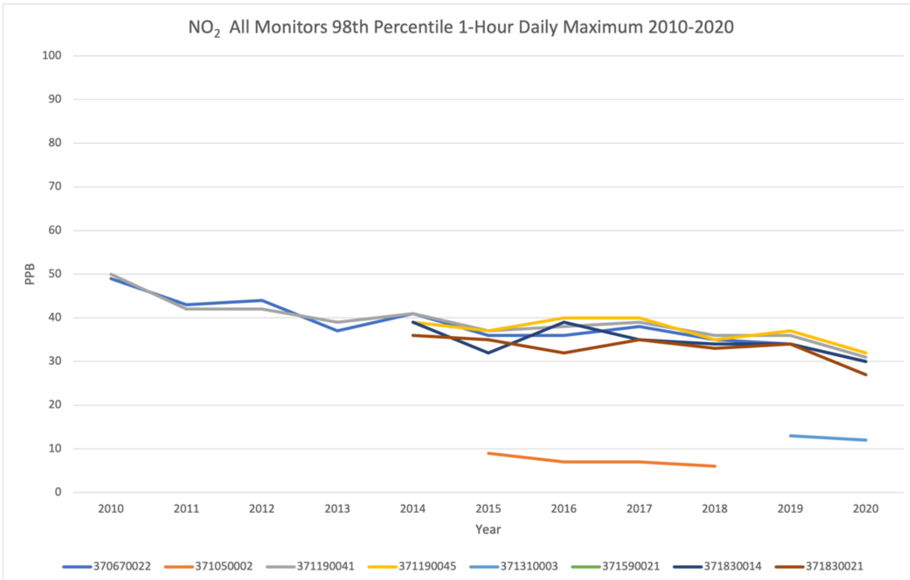

Figure 1: All annual 98th percentile values for all NO_2 monitors from 2010 to 2020

3.2. Ground-Level Ozone

The second pollutant analyzed was ground-level ozone (O_3). Figure 2 shows the values of the annual 4th highest 8-hour daily maximum values for all monitors in North Carolina from 2010-2020. O_3 shows a decrease in concentration over the eleven years: the average of all monitor's 4th highest 8-hour daily maximum value in 2010 was 0.073 ppm, with the highest value 0.082 ppm (371190041, Mecklenburg) and the lowest value 0.062 ppm (371290002, New Hanover), and the average of all monitors 4th highest 8-hour daily maximum value in 2020 was 0.055ppm, with the highest value 0.063 ppm (371990004, Yancey) and the lowest value 0.049 ppm (371170001, Martin). This overall decrease in O_3 concentrations also leads to a decrease in the design value, as that value is calculated using a three-year running average of the annual 4th highest 8-hour daily maximum values. The design value could only be calculated for the years 2012-2020, as data would have had to be collected for the years 2009 and 2008 to create design values for 2010 and 2011. The statewide average in 2012 was 0.072 ppm, and in 2020 was 0.060 ppm. The current ambient concentrations standard as provided by the NAAQS is 0.070 ppm. Currently, all monitors and the state as a whole are in attainment with the NAAQS.

There were some differences between how much each region (Mountains, Piedmont, and Coastal) decreased in their O_3 concentrations. The Mountain region saw the smallest decrease in O_3 concentrations, both in the annual 4th highest 8-hour daily maximum values and in the design values. In 2010, the average 4th highest 8-hour daily maximum value of all monitors was 0.071 ppm, with the highest monitor value 0.075 ppm (370750001, Graham) and the lowest monitor value 0.066 ppm (371730002, Swain), and in 2020 the average 4th highest 8-hour daily maximum value of all monitors was 0.056 ppm, with the highest monitor value 0.063 (371990004, Yancey) and the lowest monitor value 0.052 ppm (371139991, Macon). This is a decrease of 0.005 ppm in the average values of the annual 4th highest 8-hour daily maximum value in the Mountain region. The largest design value in 2012 came from monitor 370750001 (Graham) and had a value of 0.073 ppm, and the smallest design value came from monitor 371730002 (Swain) and had a value of 0.062 ppm. In 2020, the largest design value came from monitor 370750001 (Graham) with a value of 0.063 ppm, and the smallest design value came from monitor 371730002 (Swain) with a value of 0.057 ppm.

The Piedmont region saw larger decreases in their O_3 concentrations: in 2010, the average 4th highest 8-hour daily maximum value of all monitors was 0.075 ppm, with the highest monitor value 0.082 (371191009, Mecklenburg) and the lowest value 0.070 ppm (370370004, Chatham), and in 2020 the average 4th highest 8-hour daily maximum value of all monitors was 0.056 ppm, with the highest monitor value 0.062 ppm (370670022, Forsyth) and the lowest monitor value 0.051 ppm (371790003, Union). This is a decrease of 0.019 ppm in the average values of the 4th highest 8-hour daily maximum value in the Piedmont region. The largest design value in 2012 came from monitors 371190041 and 371191009 (both Mecklenburg) and was 0.083 ppm, and the smallest design value came from monitor 370370004 (Chatham) and was 0.065 ppm. In 2020 the largest design value came from monitor 371190041 (Mecklenburg) and was 0.067 ppm, and the smallest design value came from monitor 371239991 (Montgomery) and was 0.056 ppm. One monitor (371050002, Lee) had an increasing design value. The design value for that monitor in 2015 was 0.055 ppm, and in 2018 the design value was 0.061 ppm. This monitor only collected data from 2013-2018.

The Coastal regional falls in between the Mountain and Piedmont regions in terms of decreasing O_3 concentrations. In 2010 the average 4th highest 8-hour daily maximum value of all monitors was 0.069 ppm, with the highest monitor value 0.074 ppm (371010002, Johnston) and the lowest monitor value 0.062 ppm (371290002, New Hanover), and in 2020 the average 4th highest 8-hour daily maximum value of all monitors was 0.054 ppm, with the highest monitor value 0.056 ppm (371070004, Lenoir) and the lowest monitor value 0.049 ppm (371170001, Martin). This is a decrease of 0.015 ppm in the average values of the 4th highest 8-hour daily maximum value in the Coastal region. The largest design value in 2012 came from monitor 371010002 (Johnston) and was 0.074 ppm, and the smallest value came from monitor 370319991 (Carteret) and was 0.062 ppm. In 2020 the largest design value came from monitor 371470006 (Pitt) and was 0.061 ppm, and the smallest design value came from monitor 371170001 (Martin) and was 0.057 ppm.

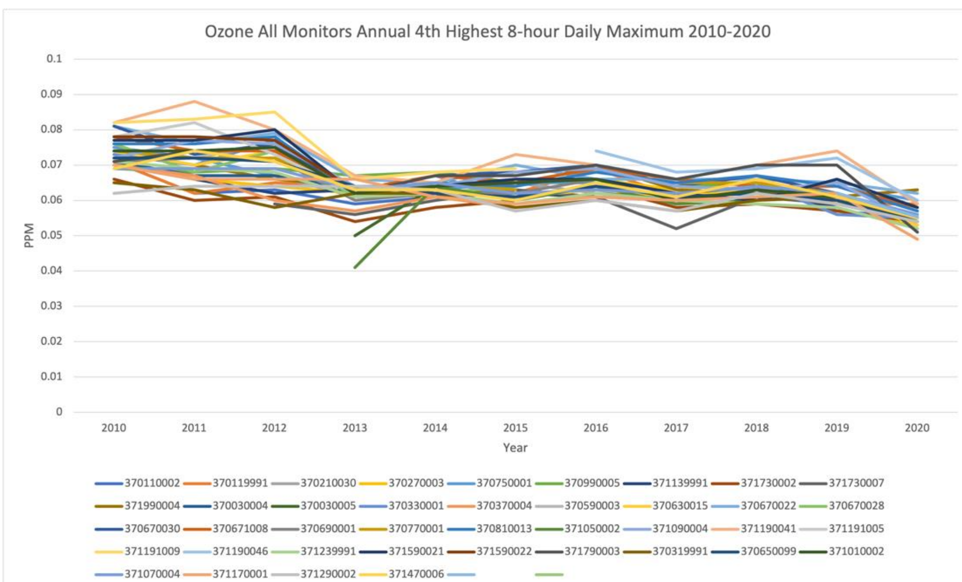

Figure 2: All annual 4th highest 8-hour daily maximum values for all O_3 monitors from 2010 to 2020

Figure 3 shows the annual 4th highest 8-hour daily maximum values, averaged for each region. The Mountain and Coastal regions show similar values to each other, with an overall decrease from 2010 to 2020, and a few increases in 2016 and 2018. The Piedmont region has more variation in its O_3 concentrations: it has the highest starting point in 2010 at 0.075 ppm, then has a big drop from 2012 to 2013, and then a general increase to a plateau through 2019. In 2020 the Piedmont region has another large drop in concentration, but still has the highest values of all three regions. Part of the reason the Piedmont saw lower concentrations in 2013 is because two monitors came online that year: monitor 370030005 (Lee) and monitor 371050002 (Alexander). The monitor in Lee county only collected data during November and December, which are not peak O_3 months as there is less sunlight, and the monitor in Alexander county only collected data from August to October. Since these monitors have fewer data collecting days in months where

O_3 is already less prevalent, statistically it will drag down the average for the whole year in the Piedmont region. Despite those monitors that came online in 2013, there were also numerous monitors that decreased from 2012 to 2013, and many of those monitors were in the Piedmont. It is impossible to know what caused this decrease from 2012 to 2013 using information from this data set alone because O_3 is a secondary pollutant (i.e., formed in the atmosphere) and can travel long distances. Looking back to individual monitors, as shown in Figure 2, there are three monitors that had concentrations much higher than the rest of the state after large spikes. These three monitors were 371190041 (Mecklenburg), 371190046 (Mecklenburg), and 371790003 (Union). After these spikes in 2019, the concentrations dropped back down to match more closely with the rest of the monitors in 2020.

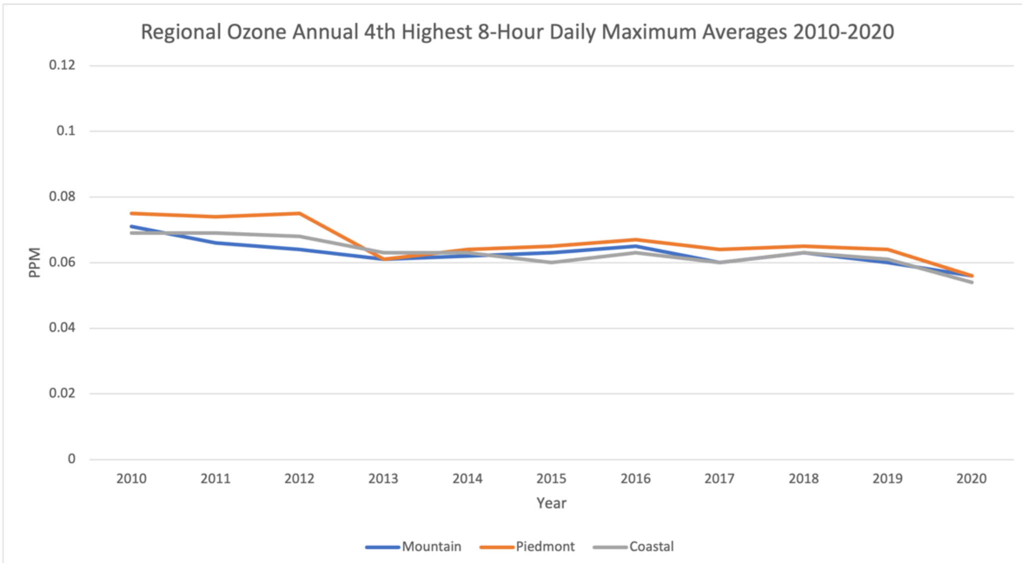

Figure 3: Regional annual 4th highest 8-hour daily maximum averages of ozone 2010-2020

3.3. Fine Particulate Matter

The third pollutant analyzed was fine particulate matter ($PM_{2.5}$). Figure 4 shows the values of the annual means for all monitors from 2010-2020. $PM_{2.5}$ shows a decrease in concentration over the eleven years: the average of all monitors annual means in 2010 was 10.0 μg/m^3, with the highest monitor value 11.8 μg/m^3 (370670022, Forsyth) and the lowest monitor value 6.6 μg/m^3 (370870035, Haywood), and in 2020 the average of all monitors annual means was 6.6 μg/m^3, with the highest monitor value 8.3 μg/m^3 (371190045, Mecklenburg), and the lowest monitor value 2.3 μg/m^3 (370870035, Haywood). This overall decrease in $PM_{2.5}$ also leads to a decrease in the design value, as that value is calculated using a three-year running average of the annual mean values. The design value could only be calculated for the years 2012-2020, as data would have had to be collected for the years 2009 and 2008 to create design values for 2010 and 2011. The statewide average of design values in 2012 was 9.3 μg/m^3, and in 2020 was 6.9 μg/m^3. The current ambient concentrations standards as provided by the NAAQS is 12.0 μg/m^3. Currently, all individual monitors and the state as a whole are in attainment with the NAAQS.

The Mountain region saw the largest decrease in $PM_{2.5}$ concentrations. In 2010 the average annual mean of all monitors was 9.3 μg/m^3, with the highest monitor value 10.6 μg/m^3 (370870012, Haywood) and the lowest monitor value 6.6 μg/m^3 (370870035, Haywood). This discrepancy between two monitors in a single county could be based on location of monitors, or how many and which data collecting days each monitor had. In 2020, the average annual mean of all monitors was 4.7 μg/m^{3,} with the highest monitor value 6.1 μg/m^3 (371730002, Swain) and the lowest monitor value 3.5 μg/m^3 (370110002, Avery). This is a decrease of 4.6 μg/m^3 in the average annual mean of all monitors in the Mountain region. The largest design value in 2012 was from monitor 370870012 (Haywood) and was 9.8 μg/m^3, and the smallest design value came from monitor 370870035 (Haywood) and was 5.8 μg/m^3. The largest design value in 2020 was from monitor 371730002 (Swain) and was 7.0 μg/m^3, and the smallest design value was from monitor 370870035 (Haywood) and was 3.2 μg/m^3. There is a large spike of $PM_{2.5}$ concentrations in 2016 – this was due to the wildfires that took place and will be discussed in a subsequent section.

The Piedmont region had the smallest decrease in $PM_{2.5}$ concentrations. In 2010 the average annual mean of all monitors was 10.6 μg/m^3 with the largest monitor value 11.8 μg/m^3 (370670022, Forsyth) and the lowest monitor value 8.9 μg/m^3 (370370004, Chatham). In 2020 the average annual mean of all monitors was 7.4 μg/m^3, with the highest monitor value 8.3 μg/m^3 (371190045, Mecklenburg) and the lowest monitor value 6.4 μg/m^3 (370810013, Guilford). This is a decrease of 3.2 μg/m^3 in the average annual mean of all monitors in the Piedmont region. The largest design value in 2012 came from monitor 370570002 (Davidson) and was 10.9 μg/m^3, and the smallest design came from monitor 370370004 (Chatham) and was 8.2 μg/m^3. The largest design value in 2020 came from monitor 371190045 (Mecklenburg) and was 8.9 μg/m^3, and the smallest design value came from monitor 370810013 (Guilford) and was 6.8 μg/m^3.

The Coastal region experienced less of a decrease in $PM_{2.5}$ concentrations than the Mountain region, but a larger decrease than the Piedmont region. In 2010 the average annual mean of all monitors was 9.4 μg/m^3, with the highest monitor value 10.8 μg/m^3 (370510009, Cumberland) and the lowest monitor value 7.1 μg/m^3 (370959000, Hyde). In 2020 the average annual mean of all monitors was 5.7 μg/m^3, with the highest monitor value 6.9 μg/m^3 (370510009, Cumberland) and the lowest monitor value 4.1 μg/m^3 (370959000, Hyde). This is a decrease of 3.7 μg/m^3 in the average annual mean of all monitors in the Coastal region. The largest design value in 2012 came from monitor 370510009 (Cumberland) and was 10.1 μg/m^3, and the smallest design value came from monitor 370959000 (Hyde) and was 6.9 μg/m^3. The largest design value in 2020 came from monitor 371010002 (Johnston) and was 7.6 μg/m^3, and the smallest design value came from monitor 371290002 (New Hanover) and was 4.3 μg/m^3. One monitor (371910005, Wayne) had an increasing design value, with its 2012 design value being 10.1 μg/m^3 and its 2015 design value being 10.7 μg/m^3. This monitor only collected data from the years 2010-2015.

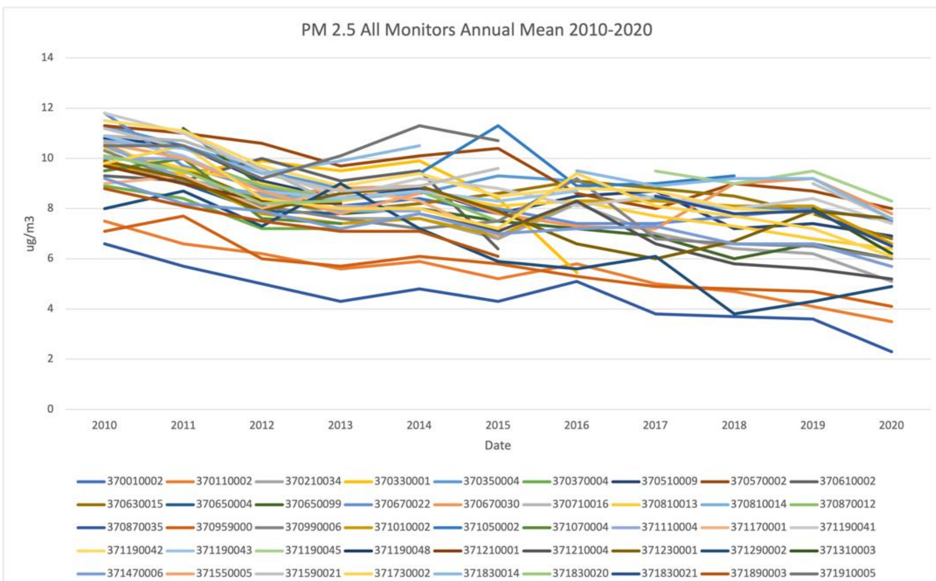

Figure 4: All annual mean values for all $PM_{2.5}$ monitors from 2010 to 2020

Figure 5 shows the differences between all annual means of $PM_{2.5}$ from 2010 to 2020, averaged for each region. All three regions overall saw a decrease from 2010 to 2020, but there is more variation between regions and patterns for $PM_{2.5}$ than there was for O_3. The Piedmont has the highest values of all three regions and does show a consistent decline in $PM_{2.5}$ concentrations, with increases seen in 2014 and from 2016 to 2019. The Coastal region also shows a large decline from 2010 to 2020, but with more variance than the Piedmont during the decade. The decline in concentration is less consistent in Coastal region than the Piedmont, with large decreases from 2011 to 2012 and 2014 to 2018, but increases in concentration in 2014 and 2019. The Mountain region has the most consistent pattern of decreasing concentrations, except for 2016. This large spike in $PM_{2.5}$ concentrations in 2016 is likely due to the wildfires that took place and will be discussed next.

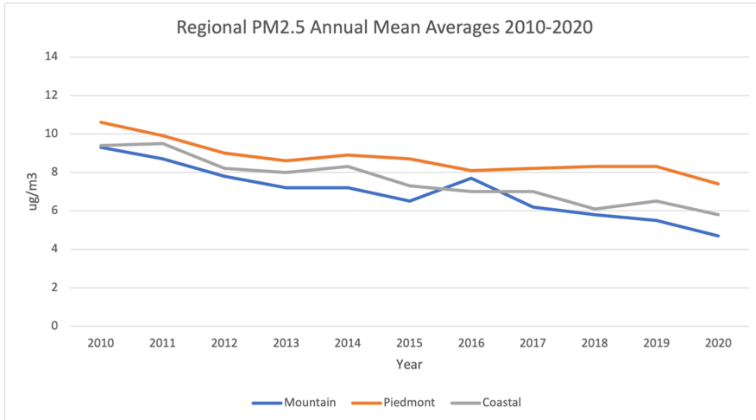

Figure 5: Regional annual mean averages of fine particulate matter 2010-2020

3.4. 2016 Wildfires

In 2016 the Mountain region saw in increase in yearly averages for $PM_{2.5}$. This is due to the wildfires that took place in November of 2016. These fires took place in largely in western North Carolina and eastern Tennessee, and at least 80,000 acres were burned. Across the state, $PM_{2.5}$ was much more abundant than normal due to the increased burning of organic matter. Figure 6 shows daily averages for each monitor in the year 2016 by region (Mountain, Piedmont, and Coastal). As shown in Figure 6, the Mountain region saw a large spike in $PM_{2.5}$ during the month of November, reaching 99.4 $\mu g/m^3$ on November 23 at monitor 371730002 (Swain). Moving eastward across the state into the Piedmont region, a spike in $PM_{2.5}$ is still seen, just to a lesser extent. In the Piedmont region the highest values of $PM_{2.5}$ were just under 54 $\mu g/m^3$ on November 14 at monitor 370350004 (Catawba), which is almost half as large as the values in the Mountain region. Moving farther east into the Coastal region and farther away from the forest fire emissions source, a spike in $PM_{2.5}$ is still seen, but again to a lesser extent than both the Mountain and Piedmont regions. The highest value of $PM_{2.5}$ reached in the Piedmont region during the forest fires was about 37.9 $\mu g/m^3$ on November 18 at monitor 371010002 (Johnston) – much less than the Mountain and Piedmont regions.

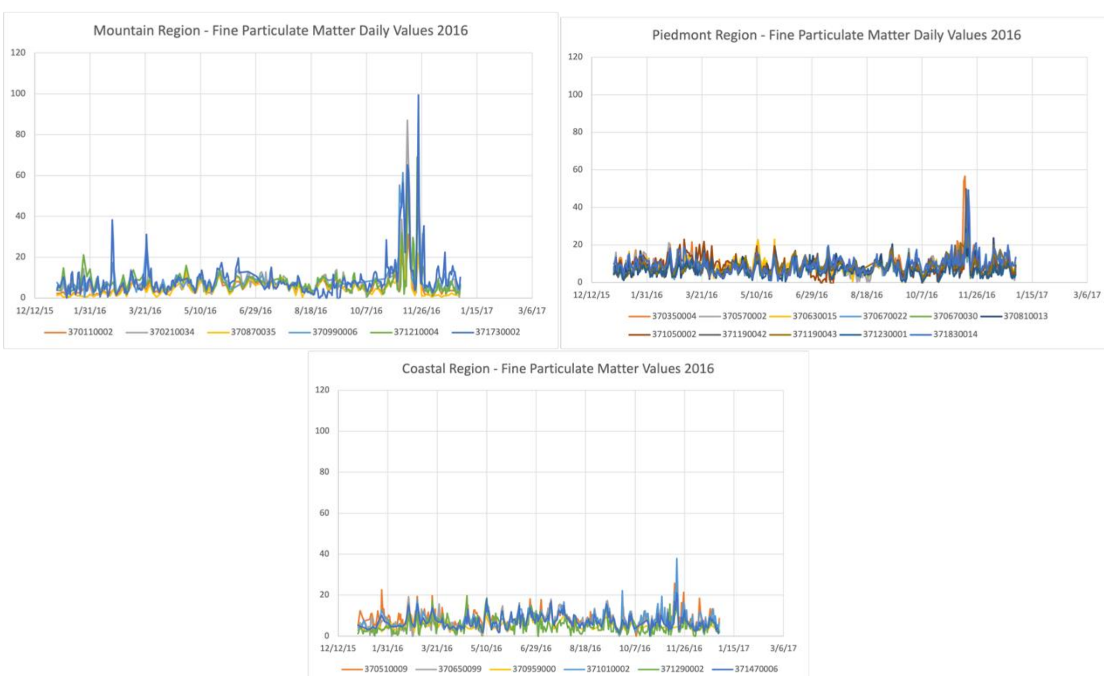

Figure 6: Daily mean values of fine particulate matter regionally during 2016

3.5. Covid-19:

The Covid-19 pandemic of 2020 also impacted air pollution across North Carolina. It was expected that the levels of air pollution would decrease more than was predicted from the previous decadal decreases in air pollution since most of the population was staying home and driving less. When looking at the pollution differences during the Covid shutdown, as shown in Table 2, 2020 shows a decrease in concentration for all three pollutants statewide. NO_2 had been trending at a concentration percentile decrease of 36.71% from 2010 to 2019, but, when the 2020 data are used, NO_2 decreased by 46.26% from 2010 to 2020. O_3 had been trending at a concentration percentile decrease of 14.81% from 2010 to 2019, then jumped to a concentration percentile decrease of 24.14% from 2010 to 2020. $PM_{2.5}$ had been trending at a concentration percentile decrease of 28.18% from 2010 to 2019, then jumped to a concentration percentile decrease of 36.41% from 2010 to 2020. This also caused a decrease in design value NO_2 and O_3.

Table 2: Percentile changes of all pollutants from 2010-2019 (left) and 2010-2020 (right)

NO2 Average Annual 98th Percentile Comparison			NO2 Average Annual 98th Percentile Comparison		
2010 Average	2020 Average	Percentile Change	2010 Average	2019 Average	Percentile Change
49.5 ppb	26.6 ppb	-46.26%	49.5 ppb	31.33 ppb	-36.71%
O3 Average Annual 4th Highest 8-Hour Max Comparison			O3 Average Annual 4th Highest 8-Hour Max Comparison		
2010 Average	2020 Average	Percentile Change	2010 Average	2019 Average	Percentile Change
0.073 ppm	0.055 ppm	-24.14%	0.073 ppm	0.062 ppm	-14.81%
PM 2.5 Average of Average Daily Means Comparison			PM 2.5 Average of Average Daily Means Comparison		
2010 Average	2020 Average	Percentile Change	2010 Average	2019 Average	Percentile Change
9.97 ug/m3	6.34 ug/m3	-36.41%	9.97 ug/m3	7.19 ug/m3	-28.18%

As seen in Table 3 the design values were calculated for 2012-2020, as well as 2012-2019 to determine the difference between a pandemic and non-pandemic pattern. For each pollutant, a state-wide average design value was calculated, and from that a regression line and equation was calculated both with and without 2020 data. The slopes of the regression lines from 2012 to 2019 were -0.74 ppb/year for NO_2, -0.002 ppm/year for O_3, and -0.40 $\mu g/m^3$ for $PM_{2.5}$. From 2012 to 2020, the regression line slope values decreased for NO_2 and O_3 to -0.96 ppb/year and -0.002 ppm/year, respectively. For NO_2, concentrations continued to decrease in 2020, but the rate of decrease increased. $PM_{2.5}$ did not have a more negative regression line slope value from 2012-2020 than from 2012-2019, with a value of -0.35 $\mu g/m^3$. This does not mean that the concentrations of $PM_{2.5}$ were not decreasing in 2020, just that they were decreasing at a slower rate than.

Table 3: Average change in design value for all pollutants from 2012-2019 (left) and 2012-2020 (right)

Pollutant	Average Change in Design Value (2012-2020)	Pollutant	Average Change in Design Value (2012-2019)
NO2	-0.957 ppb/year	NO2	-0.742 ppb/year
O3	-0.002 ppm/year	O3	-0.002 ppm/year
PM 2.5	-0.350 ug/m3/year	PM 2.5	-0.397 ug/m3/year

4. Conclusion

Air pollution is known to cause many health and environmental effects. Respiratory ailments have been caused and exacerbated by air pollution, and ecosystems damaged. In North Carolina, concentrations of air pollutants NO_2, O_3, and $PM_{2.5}$ have decreased from 2010 to 2020 on state-wide, regional, and local scales. On a state-wide scale, NO_2 concentrations have decreased by 46.26% from 2010 to 2020, O_3 concentrations have decreased by 24.14% from 2010 to 2020, and $PM_{2.5}$ concentrations have decreased by 36.41% from 2010 to 2020. There were two individual monitors to have increasing design values during this time period, but all monitors remained under the NAAQS values for each pollutant.

The wildfires of 2016 caused large amounts of $PM_{2.5}$ pollution across the state due to the increased burning of trees. The mountain region in particular saw a very large spike of $PM_{2.5}$ concentrations during the month of November. The annual mean average of $PM_{2.5}$ in the Mountain region also saw an increase due to these fires, but the Piedmont and

Coastal regions did not. The Covid-19 pandemic caused larger decreases of NO_2 and O_3 concentrations than had been seen in previous years, largely due to nationwide shutdowns and people staying home. As people stay at home more, they are driving less, which decreases the amount of air pollution that can be emitted from cars as a primary source. Overall, across the state of North Carolina, air pollution concentrations for the pollutants NO_2, O_3, and $PM_{2.5}$ have decreased from 2010 to 2020.

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