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Ozone, NOx, and $PM_{2.5}$ Sensitivity To A Coal-Fired Power Plant In Western North Carolina

Savannah Bindas
Environmental Studies - Ecology and Environmental Biology
The University of North Carolina Asheville
One University Heights
Asheville, North Carolina 28804 USA

Faculty advisor: Dr. Evan Couzo

Abstract

In January of 2020, the power plant located in Lake Julian, North Carolina, transitioned from coal to a combined-cycle natural gas power plant. Given the respective decrease in emissions associated with natural gas electricity generation as compared to coal, one can assume that the air quality in western North Carolina, where the power plant is located, was likely impacted by this transition. We examined this change in air quality using CAMx v7.10, a regional chemical transport model. Two scenarios were simulated, one with the inclusion of the coal-fired power plant (basecase), and another with the powerplant removed from the simulation (zeroout). We estimated the power plant's impact on air quality by analyzing the difference between these two scenarios. Three major pollutants were analyzed: ozone (O_3), NOx, and fine-scale particulate matter ($PM_{2.5}$). Three species of $PM_{2.5}$ were also analyzed: SO_4, NO_3, and NH_4. Results show a calculable positive difference between the basecase and the zeroout scenarios for ozone, NOx, and $PM_{2.5}$, meaning that the basecase scenario had larger pollutant concentrations than the zeroout scenario. There is a 1-hr maximum difference of up to 2.5 ppb for ozone, up to 2.0 ppb for NOx, and up to 0.9 $\mu g/m^3$ for $PM_{2.5}$. We have also found that the ozone difference is largest during ozone season, as compared to the annual values. Maximum differences for all three pollutants occur within 24km from the powerplant.

1. Introduction

Following the passage of the 1970 Clean Air Act, ambient air quality in the United States has greatly improved, with criteria and precursor pollutants such as ozone (O_3) and fine-scale particulate matter ($PM_{2.5}$) dropping by 77%[16]. This is associated with many positive effects both economically and socially, including improved lung function in children[8] and an extended overall life expectancy[2]. Although air quality in the United States has improved, O_3 and $PM_{2.5}$ remain a major public health concern, due to the risk of premature mortality and economic losses, particularly associated with $PM_{2.5}$[9]. The estimated economic cost of lost work days and hospitalizations caused by these two pollutants in 2016 in the United States was $21 billion[12]. In 2005, $PM_{2.5}$ and O_3 were responsible for between 130,000 and 340,000 premature deaths and 4.3 million lost workdays[5,6]. Of the total years of life lost to $PM_{2.5}$ in 2016, ~26% is attributable to electricity generation, likely because of the impact of coal-fired power plants[6].

While the use of coal as an energy source has declined from over 1 billion short tons in 2000 to <600 million short tons in 2019, it was still responsible for 21.8% of the electricity generated in 2021[19,7]. Electricity generation, particularly from coal, is responsible for large emissions of both $PM_{2.5}$ and NOx, which is a precursor to O_3[14]. The emissions of NOx from coal power plants lead to the formation of O_3 in the atmosphere[3,18], and the emissions of even relatively small coal-fired power plants are associated with significant concentrations of $PM_{2.5}$ and O_3 in the communities surrounding a power plant[13]. Understanding the impact of these single sources is important in order to inform air quality management strategies, especially as it concerns State Implementation Plans (SIPs) and emissions trading among sources[11].

In recent years, the percentage of electricity generated via coal-fired power plants in the US has been steadily decreasing, and the fraction of electricity generated via combined-cycle natural gas plants has been increasing[20]. Domestic use of natural gas for electricity generation doubled between 2005 and 2020[21]. This is due to advancements made in directional drilling and horizontal fracturing, leading to a decrease in the price per unit of fuel to generate electricity from a natural gas source and a reduction in the competitiveness of coal-fired power plants in many places in the US[17]. Natural gas plants emit far less NOx and SO_2 per unit of fuel; there is an estimated 40% decrease in NOx emissions and a 44% decrease in SO_2 emissions from natural gas power plants[4]. Researchers also point to the use of natural gas power plants as a means to limit the emissions of CO_2, and therefore control the impact of electricity generation on climate change[15].

Air quality models are an appropriate method for determining the impact of single sources on regional air quality[10,11,18,1]. Particularly, the use of Eulerian photochemical grid models, such as the Comprehensive Air Quality Model with Extensions (CAMx) and the Community Multiscale Air Quality model (CMAQ), to determine the impact of single sources on air quality has been well established[10,11,18,1]. Eulerian grid models are capable of creating a chemical and physical environment within a three-dimensional grid domain, which allows the model to make predictions regarding the concentrations of primary and secondary pollutants associated with single-sources[18,1,11]. The most straightforward approach to estimate the impact from a power plant using an Eularian grid model is the brute-force (BF) sensitivity method[11]. This approach involves the use of two simulations, where the impact of the plant is estimated by "zeroing out" the power plant and subtracting the results from this scenario from the one where the plant was included[11]. The BF method is an established way to obtain estimates of regional impacts on air quality[10,11,1] but it is a more time-consuming and data heavy approach, as compared to other sensitivity methods, such as DDM or HDDM[11,3].

This study looks at the impact of a single-source coal fired power plant on air quality in western North Carolina. The Lake Julian power plant, located in western North Carolina, transitioned from a 340 MW coal fired power plant to a 560 MW combined cycle natural gas power plant in January of 2020. Given the respective decrease in emissions associated with natural gas power plants, we expect to see a change in air quality in the area surrounding the power plant. Using the BF sensitivity method, we were able to quantify the change in air quality associated with this transition.

2. Methods

The sensitivity of emissions to the Lake Julian power plant was determined using a chemical transport model. The model used for this study was CAMx version 7.10 which simulated air quality for the continental United States, using information from the EPA's 2016v1 National Emissions Collaborative Modeling Platform and the carbon bond v6 (r4) chemical mechanism. Point source and area emissions were modeled using 2016 as the base year and based on the 2016 National Emissions Inventory. The model has a horizontal grid resolution of 12x12 km extending across the continental United States, (Figure 1a, 1b). The analysis domain for this study was 50x70 grid cells, centered around western North Carolina where the power plant is located. Only the first vertical layer was analyzed in this study. The model ran for 366 days in the year 2016.

Figures 1a and 1b. Maps showing the entire domain on the left and the analysis domain used on the right

In order to determine the impact of the power plant in Lake Julian, the brute-force (BF) sensitivity method was used. This involves two scenarios, a basecase and a zeroout. The basecase scenario is run with the inclusion of the emissions from the power plant, and the zeroout scenario is run with those emissions removed. The scenarios can then be subtracted from each other in order to determine the impact of this point source. Since the zeroout scenario completely removes the emissions from the power plant, it differs from the reality of the situation, where the power plant changes from a coal to a combined-cycle natural gas plant. This approach ignores the face that there is NOx and other O_3 precursor pollutants emitted from natural gas power plants. However, given the reduction in emissions associated with natural gas, this approach provides an estimate of the air quality impact of this transition[4].

This study focused on three pollutants: NOx, O_3, and $PM_{2.5}$. Total $PM_{2.5}$ was determined by adding up the concentrations of particulate sulfate (PSO_4), particulate nitrate (PNO_3), particulate ammonium (PNH_4), Primary Organic Aerosols (POAs), Secondary Organic Aerosols (SOAs), Primary Elemental Carbon (PEC), Fine Other Primary (FPRM), Fine Crustal (FCRS), sodium (NA), and particulate chloride (PCL). PSO_4, PNO_3, and PNH_4 were responsible for the majority of $PM_{2.5}$ emissions from the power plant, so additional analysis was conducted for these species. The annual mean daily max (AMDM) was determined for the basecase and zeroout scenarios for NOx, O_3, $PM_{2.5}$, PSO_4, PNO_3, and PNH_4. The AMDM difference for these pollutants was also determined by subtracting the AMDM zeroout values from the ADMD basecase values. For O_3, the seasonal mean daily max (SMDM) values for the basecase and zeroout scenarios were determined in order to reflect the impact during ozone season (March-Oct). The SMDM difference values were calculated by subtracting the SMDM zeroout from the SMDM basecase.

Additional analysis was performed in order to determine the impact of wind direction on differences between the basecase and zeroout scenarios. To determine the role of wind direction, the analysis domain was split into 5 flow sectors based on the direction of a visible plume of ozone difference >0.25 ppb. Sector 1 includes all the days where the ozone plume appeared to flow to the west, sector 2 to the northwest, sector 3 to the northeast, sector 4 to the southeast, and sector 5 to the southwest (Figure 2). Sector 2 includes the largest city in western North Carolina, Asheville, which is also a grid cell of interest for this study, so understanding how often the difference plume flowed into that sector helps determine which areas would be most impacted by the Lake Julian power plant. These sectors were also used to determine the difference concentrations of O_3, NOx, and $PM_{2.5}$ as a function of distance from the emissions source.

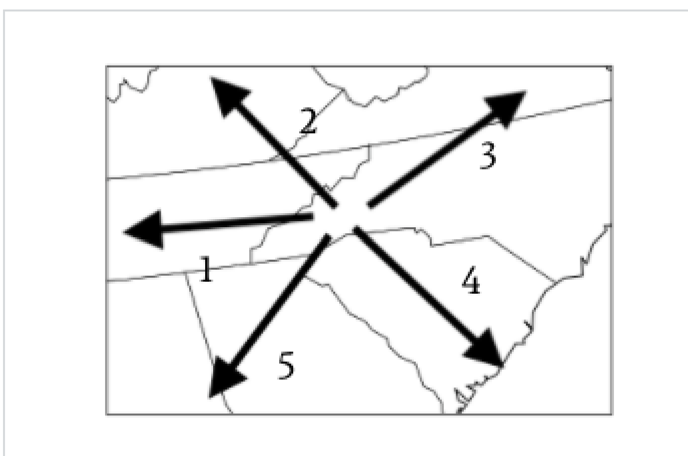


Figure 2. Map showing the analysis domain split into 5 flow sectors: sector 1 to the west, sector 2 to the northwest, sector 3 to the northeast, sector 4 to the southeast, and sector 5 to the southwest.

3. Results and Discussion

The largest differences between basecase and zeroout for NOx, O_3, and $PM_{2.5}$ across the analysis domain were all found close to the emissions source in western North Carolina (Figures 3a, 3b, 3c). The largest 1-hr difference between the basecase and zeroout scenarios was 1.65 ppb for NOx, 2.47 ppb for O_3 and 0.87 $\mu g/m^3$ for $PM_{2.5}$. The differences between the basecase and zeroout scenarios across the entire analysis domain are all positive, indicating that throughout the analysis domain the basecase had higher concentrations of NOx, O_3, and $PM_{2.5}$ (Table 1). The annual mean daily max (AMDM) difference for NOx was 0.001 ppb and for $PM_{2.5}$ was 0.002 $\mu g/m^3$ (Table 1). The differences between the basecase and the zeroout for O_3 changed depending on whether the entire year was analyzed. For the ozone season, the seasonal mean daily max (SMDM) difference was 0.004 ppb and the AMDM difference was 0.002 ppb. The ozone season values are double the values across the entire year, which matches expectations because there is a larger potential for ozone chemistry to occur during ozone season,increasing the likelihood that NOx from the power plant can turn into O_3. All of the AMDM values are relatively small, but these differences are calculated across the entire analysis domain; a large area that measures 600x900km, so smaller values are to be expected considering most differences are found near the power plant's location. The emissions from one smaller power plant are diluted across the entire analysis domain, meaning that smaller differences are to be expected. Figure 1c does show a noticeable difference for $PM_{2.5}$ further away from the source, in the northern Alabama region. Through analysis of the different species of $PM_{2.5}$ simulated in this study, it was determined that these abnormalities are likely the result of numerical errors associated with PNO_3, although the reason for these differences in that region is unclear.

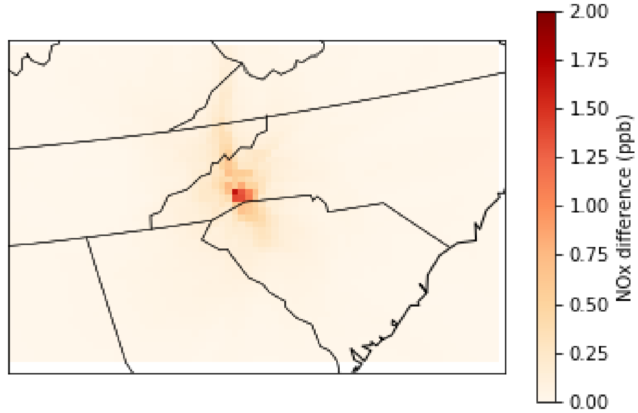


Figure 3a. Time-unpaired map showing maximum NOx difference between basecase and zeroo
ut for analysis domain. Differences within grid cells are time-paired but differences across grid cells are not.

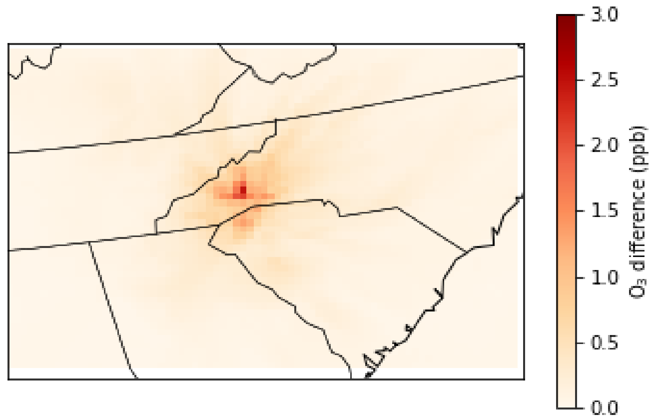


Figure 3b. Time-unpaired map showing maximum O_3 difference between basecase and zeroout for analysis domain. Differences within grid cells are time-paired but differences across grid cells are not.

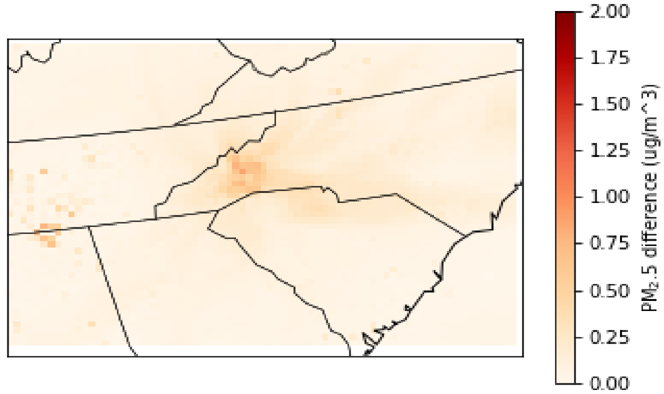


Figure 3c. Time-unpaired map showing maximum $PM_{2.5}$ difference between basecase and zeroout for analysis domain. Differences within grid cells are time-paired but differences across grid cells are not.

Table 1. Table showing the daily max time-paired basecase, zeroout, and difference AMDM for NOx, O_3, and $PM_{2.5}$ for the entire analysis domain and SMDM for O_3 for the entire analysis domain

	NOx Annual Mean Daily Max (ppb)	O_3 Annual Mean Daily Max (ppb)	O_3 Ozone Season Mean Daily Max (ppb)	$PM_{2.5}$ Annual Mean Daily Max (μg/m^3)
Basecase	5.599	44.038	49.095	16.373
Zeroout	5.598	44.035	49.091	16.371
Difference (bc-zo)	0.001	0.002	0.004	0.002

The values in Tables 2 and 3 show the AMDM differences for NOx and $PM_{2.5}$ and the ozone SMDM values for O_3 within two grid cells of interest. Those grid cells are the cell where the power plant was located, Lake Julian, and nearby Asheville. The city of Asheville was chosen as a grid cell of interest because of the population's exposure to the Lake Julian power plant. The mean daily max difference values for all species are much higher than the values in Table 1, indicating that the largest differences are found closest to the source of the emissions and become more diffuse across the entire analysis domain. The SMDM for O_3 match differences for a power plant of a similar size to Lake Julian studied in Martenies et al. (2019). A power plant the size of the one located in Lake Julian does have an impact, especially on local air quality, but annual mean daily max differences are expected to be relatively small. It is important to distinguish that while although the values are small, the difference values are in Tables 2 and 3 are much larger than the differences found in Table 1, which analyzed the entire analysis domain. Additionally, the differences in the Asheville grid cell are larger than those in the Lake Julian grid cell. This is likely due to the fact that only the ground layer of the model was analyzed. The emissions of the power plant in the Lake Julian grid cell were injected above the first vertical layer, so it is not surprising that we find larger values further from the emissions source. Additionally, the chemistry needed to create O_3 and secondary $PM_{2.5}$ takes time, which also helps explain why larger values were found in the Asheville grid cell instead of the grid cell where the power plant is located.

Table 2. Table showing the AMDM basecase, zeroout, and differences for NOx (ppb) and $PM_{2.5}$ ($\mu g/m^3$) and the SMDM basecase, zeroout, and differences for O_3 (ppb) for the Lake Julian grid cell

	NOx Annual Mean Daily Max Lake Julian (ppb)	O_3 Ozone Season Mean Daily Max Lake Julian (ppb)	$PM_{2.5}$ Annual Mean Daily Max Lake Julian ($\mu g/m^3$)
Basecase	12.636	50.799	13.139
Zeroout	12.622	50.695	13.124
Difference (bc-zo)	0.015	0.105	0.015

Table 3. Table showing the AMDM basecase, zeroout, and differences for NOx (ppb) and $PM_{2.5}$ ($\mu g/m^3$) and the SMDM basecase, zeroout, and differences for O_3 (ppb) for the Asheville grid cell

	NOx Annual Mean Daily Max Asheville (ppb)	O_3 Ozone Season Mean Daily Max Asheville (ppb)	$PM_{2.5}$ Annual Mean Daily Max Asheville ($\mu g/m^3$)
Basecase	10.789	50.120	12.949
Zeroout	10.770	50.056	12.933
Difference (bc-zo)	0.018	0.064	0.017

July 21, 2016, was the day of maximum difference for both the entire analysis domain and for the two grid cells of interest for NOx and O_3. The peak NOx values occur at 6 a.m. (Figure 4a, 4b). However, the largest differences occur at approximately 8am for both the Lake Julian and Asheville grid cells: a 0.55 ppb difference at 9 a.m. in Lake Julian and a 0.39 ppb difference at 8 a.m. in Asheville (Figure 4a, 4b). While July 21, 2016, is the day of maximum difference for these two grid cells, the largest difference occurs somewhere else in the analysis domain. Figure 5 shows that this difference still occurs very close to the source of emissions. At 7 a.m. on July 21, 2022, a grid cell near the emissions source showed a difference of 1.65 ppb (Figure 5). Even though the largest difference did not occur within the Lake Julian or Asheville grid cells, it still occurs in an area south of the emissions source. There are two peaks for O_3 on July 21, 2016, the first occurring around 10 a.m. and again around 6 p.m. (Figures 6a, 6b). The largest difference for both the Lake Julian and the Asheville grid cells occur at 10 a.m.: a 2.47 ppb difference at 10 a.m. in Lake Julian and a 1.49 ppb difference at 10 a.m. in Asheville (Figures 6a, 6b). Unlike NOx, the maximum difference across the entire analysis domain did occur within the Lake Julian grid cell (Figure 7).

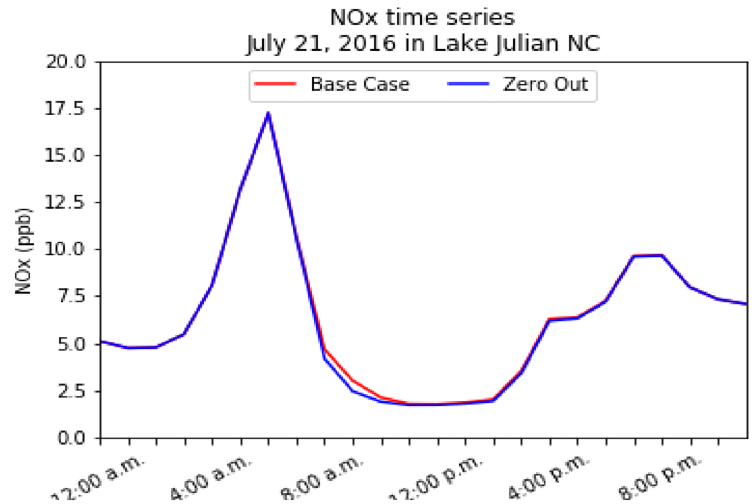


Figure 4a. Time series showing the basecase and zeroout values for NOx (ppb) for the day of maximum difference (July 21, 2016) within the Lake Julian grid cell

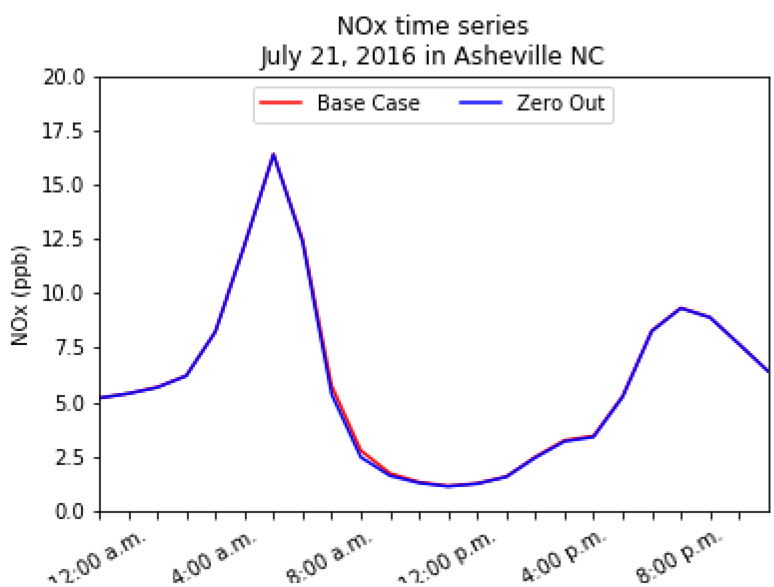


Figure 4b. Time series showing the basecase and zeroout values for NOx (ppb) for the day of maximum difference (July 21, 2016) within the Asheville grid cell

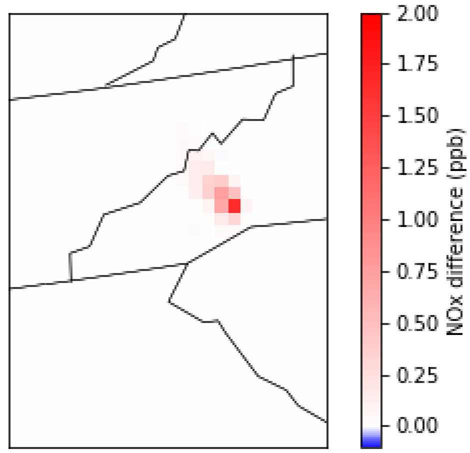


Figure 5. Map showing the day of maximum difference for NOx (ppb) (July 21, 2016) at the time of maximum difference (7am)

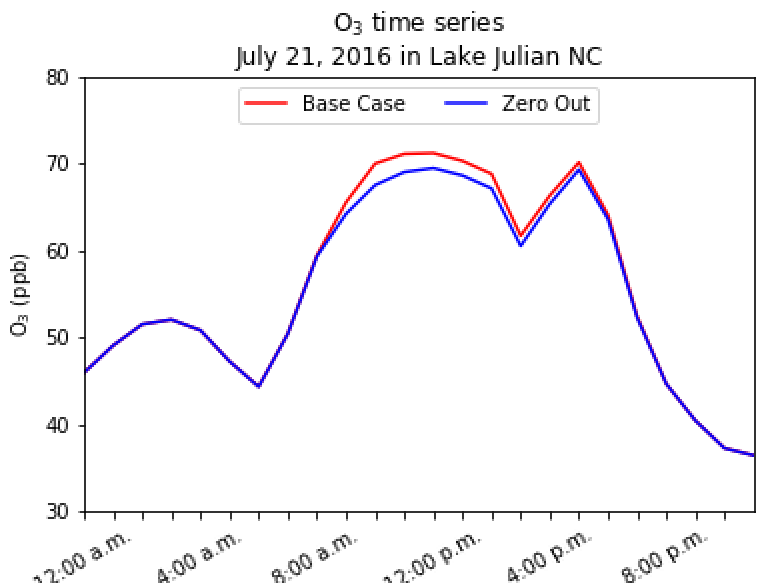


Figure 6a. Time series showing the basecase and zeroout values for O_3 (ppb) for the day of maximum difference (July 21, 2016) within the Lake Julian grid cell

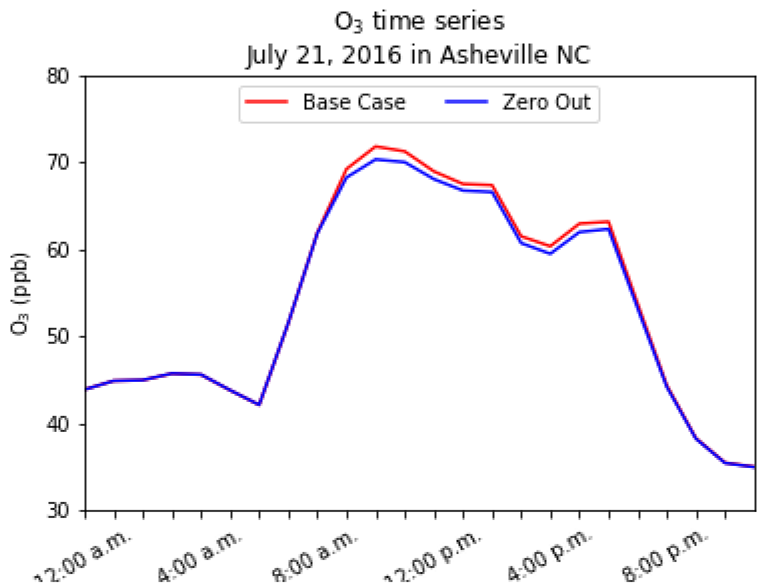


Figure 6b. Time series showing the basecase and zeroout values for O_3 (ppb) for the day of maximum difference (July 21, 2016) within the Asheville grid cell

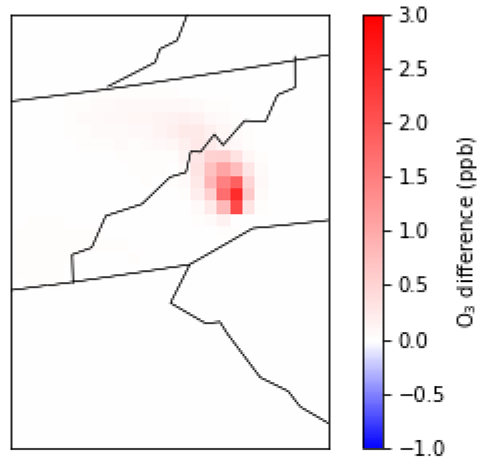


Figure 7. Map showing the day of maximum difference for O_3 (ppb) (July 21, 2016) at the time of maximum difference (10am)

The day of maximum difference for total $PM_{2.5}$ was Nov 1, 2016. There were two peaks for $PM_{2.5}$, the first occurring at 7 a.m. and the second at the end of the day (Figures 8a, 8b). The peak differences occurred at 7 a.m. in both the Lake Julian and Asheville grid cells (Figures 8a, 8b). PNO_3 values follow closely the trend of total $PM_{2.5}$, peaking at 7 a.m. and at the end of the day. The other species included in these figures, PSO_4 and PNH_4, also show peaks especially at 7 a.m., but indicate less of a dip in values during the middle of the day as compared to PNO_3 and total $PM_{2.5}$ (Figures 8a, 8b). Table 4 shows the AMDM for basecase, zeroout, and difference for the three PM species included in Figures 8a and 8b: PSO_4, PNO_3, and PNH_4. It also included the percentage that each species contributed to the AMDM of total $PM_{2.5}$. PSO_4 was found to have the largest difference, 0.001 $\mu g/m^3$, and is also responsible for 50% of the total PM2.5 difference, much larger than either of the other two PM species. PNO_3 had the largest AMDM values, 2.219 $\mu g/m^3$ and 2.220 $\mu g/m^3$, which is double the values for PNH_4. However, neither PNO_3 nor PNH_4 contributed more than 15% to the difference for total PM. Figure 9 shows the entire analysis domain on the day of maximum difference (Nov 1, 2016) at the time of maximum difference within the domain (7 a.m.). Somewhere north of the emissions source at 7 a.m. on Nov 1, 2016, the maximum difference was 0.88 μg/m^3. Figure 9 also indicates slight negative values close to the source of emissions, indicating that the zeroout scenario actually had larger $PM_{2.5}$ values in some grid cells. On Nov 1, 2016, PSO_4 had a minimum difference of -0.118 μg/m^3, PNO_3 had a minimum difference of -0.047 μg/m^3, and PNH_4 had a minimum difference of -0.044 μg/m^3. These values show that PSO_4 contributed most significantly to the larger zeroout values found close to the source of the emissions in Figure 9.

Table 4. Table showing the AMDM basecase, zeroout, and difference values for the 3 most important $PM_{2.5}$ species: PSO_4, PNO_3, and PNH_4. For basecase and zeroout, the percentages show fractional PM composition by mass and for the difference, the percentage shows the percentage of the total difference attributable to each species. The PNO_3 and PNH_4 differences appear as 0.000 because of rounding.

	PSO_4 (μg/m^3)	PNO_3 (μg/m^3)	PNH_4 (μg/m^3)
Basecase	1.891 (11.5%)	2.219 (13.5%)	1.021 (6.2%)
Zeroout	1.890 (11.5%)	2.219 (13.5%)	1.021 (6.2%)
Difference (bc-zo)	0.001 (50%)	0.000 (10%)	0.000 (15%)

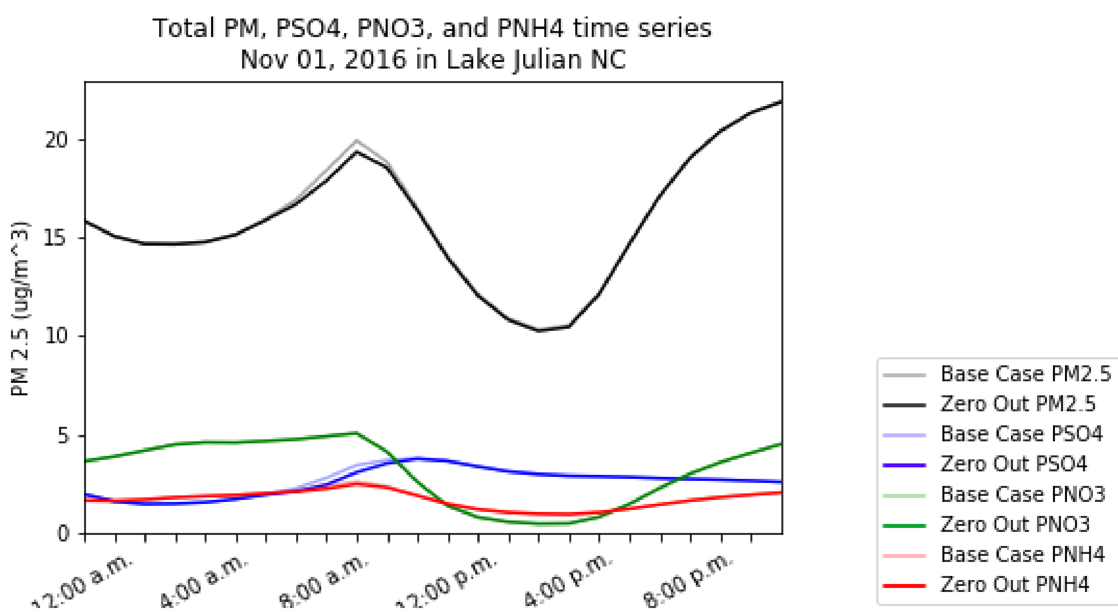
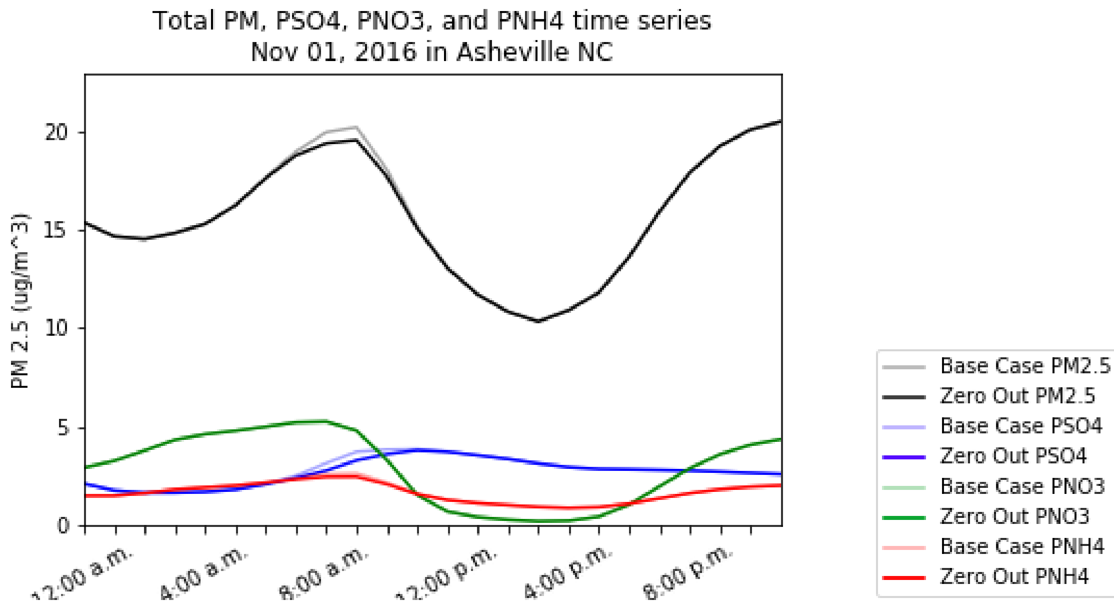


Figure 8a. Time series showing the bascase and zeroout values for total $PM_{2.5}$, PSO_4, PNO_3, and PNH_4 (μg/m^3) for the day of maximum difference (Nov 1, 2016) in the Lake Julian grid cell



Figures 8b. Time series showing the basecase and zeroout values for total $PM_{2.5}$, PSO_4, PNO_3, and PNH_4 ($\mu g/m^3$) for the day of maximum difference (Nov 1, 2016) in the Asheville grid cell

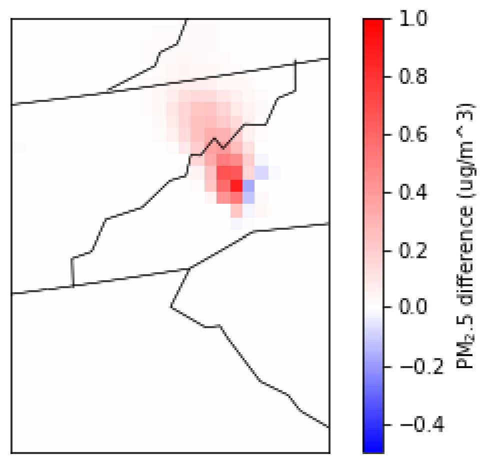


Figure 9. Map showing the day of maximum difference for $PM_{2.5}$ ($\mu g/m^3$) (Nov 01, 2016) at the time of maximum difference (7am)

Figures 10a-e provide a visual representation of the 5 sectors of the analysis domain used as proxy for wind direction. Sector 1 had 4 days, sector 2 had 45, sector 3 had 49, sector 4 had 19, and sector 5 had 7. Sectors 2 and 3 had the most days, indicating that wind more often flowed either in the NE or NW direction when there was an O_3 difference plume of >0.25 ppb. There were a total of 124 days in 2016 included in these sections, meaning there were 124 days with an O_3 difference >0.25 ppb, starting on March 6th and ending on November 17th. These days were mostly clustered in the summer months; from July 21st to September 16th there was not a single day with an O_3 difference <0.25 ppb. Sector 2 had the largest 1-hr difference for NOx, 0.271 ppb. Sector 1 had the largest 1-hr difference for O_3, 0.835 ppb. Sector 1 also had the largest 1-hr difference for $PM_{2.5}$, 0.274 $\mu g/m^3$. Maximum differences across all 5 sections during 2016 for NOx, O_3, and $PM_{2.5}$ are shown to occur within the 12-24km (1-2 grid cells) closest to the emissions source (Figure 11a, 11b, 11c). These results match results found by Kelly et al. (2015) and Goodkind et al. (2019), both of which found the largest impacts from a single source to be within the 24km (2 grid cells) closest to the emissions source. Peak values for all three pollutants most often occur 12km from the power plant.

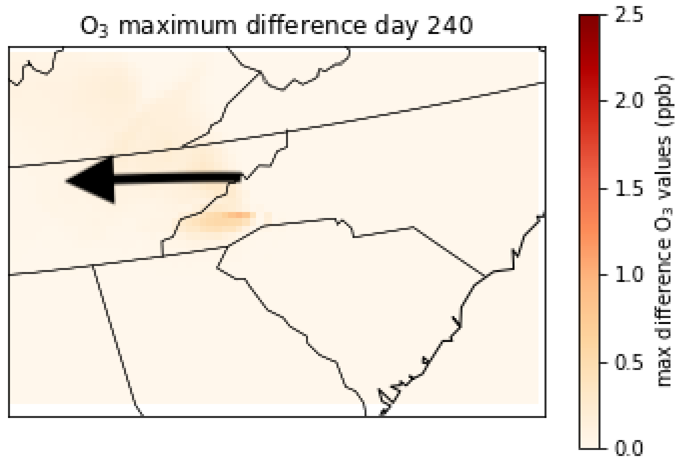


Figure 10a. Map showing the ozone plume flowing into sector 1 (W), which includes 4 days or 3.2% of the total days included

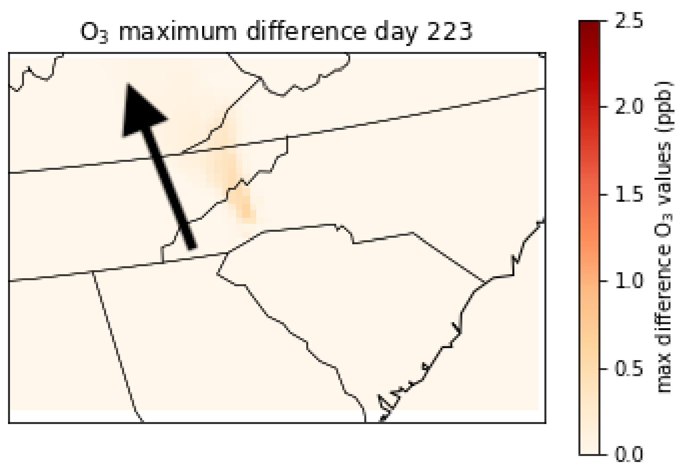


Figure 10b. Map showing ozone plume flowing into sector 2 (NW), which includes 45 days, or 36.3% of the total days included

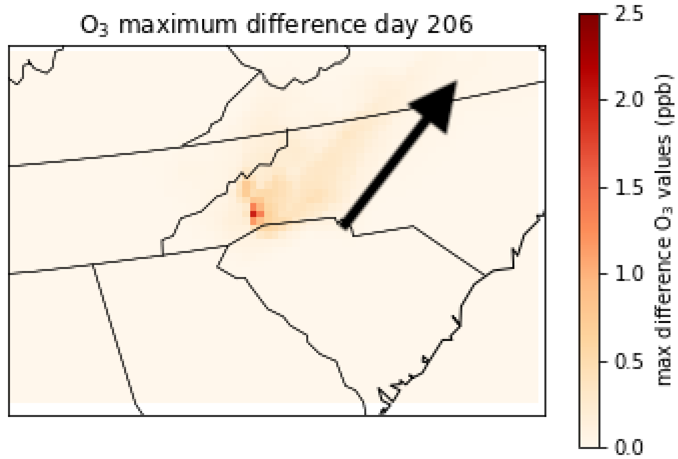


Figure 10c. Map showing the ozone plume flowing into sector 3 (NE), which includes 49 days, or 39.5% of the total days included

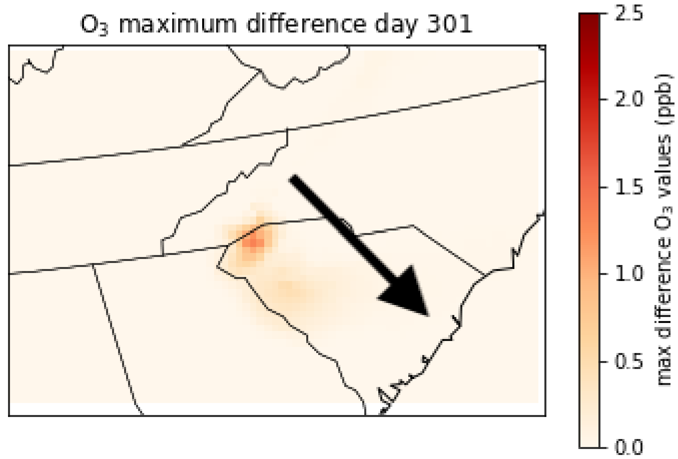


Figure 10d. Map showing the ozone plume flowing into sector 4 (SE), which includes 19 days, or 15.3% of the total days included

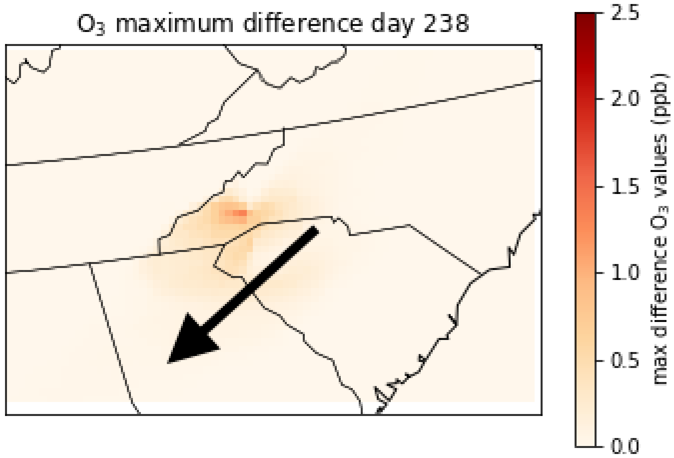


Figure 10e. Map showing the ozone plume flowing into sector 5 (SW), which includes 7 days, or 5.6% of the total days included

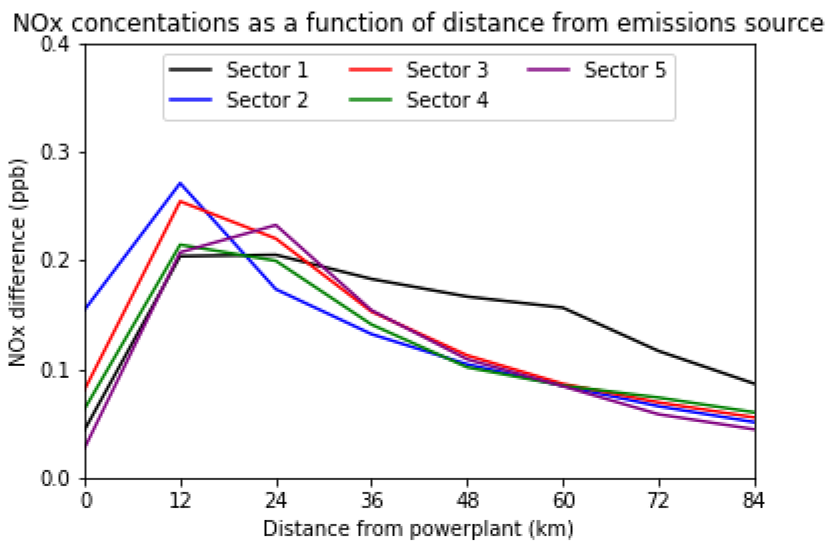


Figure 11a. Figure showing NOx difference concentrations (ppb) as a function of distance from the emissions source for all 5 sections

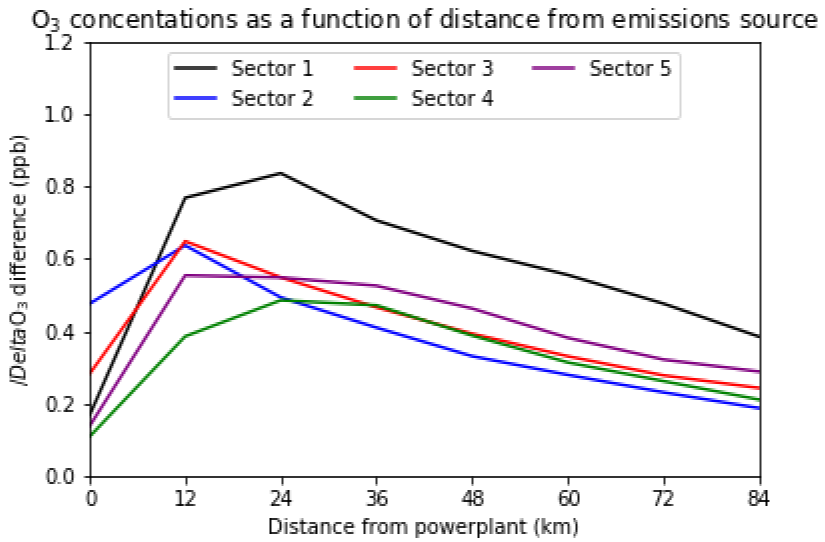


Figure 11b. Figure showing O_3 difference concentrations (ppb) as a function of distance from the emissions source for all 5 sections

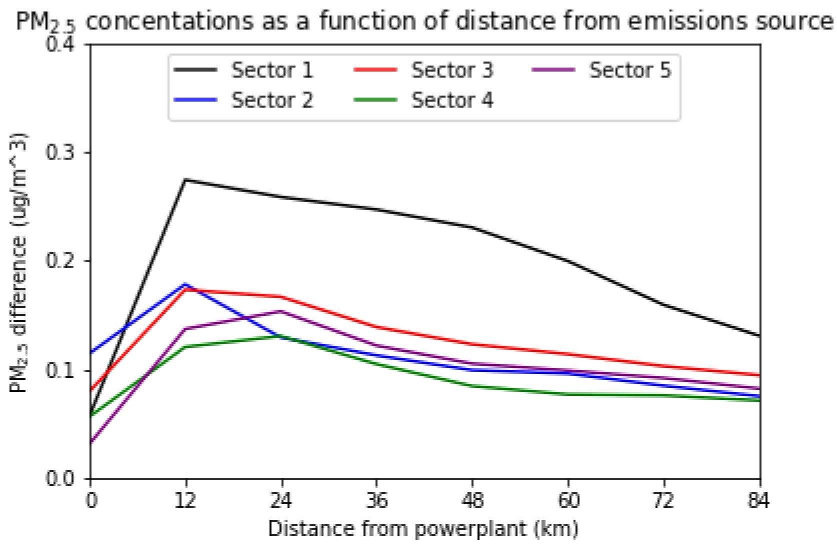


Figure 11c. Figure showing $PM_{2.5}$ difference concentrations ($\mu g/m^3$) as a function of distance from the emissions source for all 5 sections

4. Conclusion

In January or 2020, the coal fired power plant located in Lake Julian, North Carolina, transitioned to a combined cycle natural gas power plant. The impact of the Lake Julian power plant on air quality in western North Carolina was determined using the BF sensitivity method in conjunction with the CAMx chemical transport model. We estimated the changes in air quality associated with the power plant's transition from coal to natural gas in January of 2020. There were positive differences found between the basecase and zeroout scenarios for each pollutant analyzed: O_3, NOx, and $PM_{2.5}$. The largest 1-hr difference for NOx was 1.47ppb, O_3 was 2.47ppb, and $PM_{2.5}$ was 0.87$\mu g/m^3$. These differences were similar in magnitude to those found by Martenties et al. (2019), which looked at a power plant similar in size to the one located in Lake Julian. O_3 SDMD difference was also double the AMDM O_3 difference, indicating that the impact of this power plant on O_3 was highest during ozone season. These differences are an upper limit estimate of the impact of this power plant's transition, given that the model did not simulate natural gas emissions.

The largest differences for each pollutant were found within 1-2 grid cells (12-24 km) from the emissions source, which shows that the largest air quality impacts associated with this transition occurred near Lake Julian, North Carolina. These results match those found by both Kelly et al. (2015) and Goodkind et al. (2019), which showed the largest impact of emissions within 12-24km (1-2 grid cells) from the source of emissions. Overall, the results show that the air quality in western North Carolina is impacted by the Lake Julian power plant, and the transition of this power plant from coal to natural gas was likely associated with a decrease in certain pollutants, especially O_3 and $PM_{2.5}$.

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6. References

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