PITTSBURGH AND AIR POLLUTION: A STUDY OF CRITERIA GASES AND PARTICULATE MATTER DURING THE COVID-19 LOCKDOWN

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ABSTRACT

The COVID-19 pandemic and early mitigation efforts of stay-at-home periods have offered a unique opportunity to study anthropogenic pollution. Poor air quality affects human health, and COVID-19 can exacerbate existing respiratory conditions. The Greater Pittsburgh Metropolis (Allegheny County, Pennsylvania) has experienced poor air quality throughout its history, and this makes Pittsburgh an ideal location to study pollution trends. Using ground-based Environmental Protection Agency AirData at four locations with varied socioeconomic statuses within Allegheny County, nitrogen dioxide (NO_2), sulfur dioxide (SO_2), ozone (O_3), and particulate matter with aerodynamic diameter less than 2.5 μm ($PM_{2.5}$) were observed for pre-, during, and post-COVID-19 trends. The datasets exhibit a reduction of pollutants during the COVID-19 period. Post-COVID levels rebounded to pre-COVID levels, theorizing anthropogenic pollution trends. These trends are consistent with NO_2 and SO_2 measurements from the space-based Tropospheric Monitoring Instrument (TROPOMI) data. Meteorological variants provided from AirData such as wind and temperature were analyzed and compared with the pollutant gases, however no conclusive relationship could be found with this data. This study can open the benefits of dual monitoring for pollution trends and COVID-19 while engaging possibilities on modifying human activities to reduce pollutants.

1. INTRODUCTION

In 2020, the novel coronavirus disease (COVID-19) global pandemic and subsequent containment measures caused a disruption to human activities. To mitigate the spread of the virus, local and state governments in the United States issued stay-at-home orders and only allowed essential businesses to operate. These stay-at-home timeframes varied by location and created a unique opportunity to observe trends in air quality and anthropogenic pollution in a natural laboratory. Air quality is important to human health as poor air quality leads to respiratory illness and increases COVID-19 comorbidity (Ali et al., 2021).

Pittsburgh has a long history of poor air quality since its inception in the early 1750s when the first coal seam was found near Mt. Washington. By the 1800s, the city was known as “hell with the lid taken off” with Pittsburgh’s unique geographic location and topography containing much of the coal smoke produced from the industries on the rivers in the valleys (Davidson, 1979). Despite the city enacting air quality ordinances in the early 1900s, Pittsburgh residents lacked clean air through the events of the Donora Smog of 1948. The Donora Smog caused 21 mortalities and over 5,000 people to suffer respiratory illnesses and infections over the course of three days (Davidson, 1979). Being one of the worst air pollution disasters in the United States, this event helped initiate public demand for cleaner air both local and nationwide. That public demand eventually led to The Clean Air Act’s establishment in 1970, with major revisions in 1977 and 1990 (US EPA, 2021).

Air pollution exposure is responsible for millions of deaths worldwide according to the World Health Organization (WHO, 2021). Notably, lower socioeconomic areas have higher

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incidences of respiratory illnesses and morbidity, as these areas are often affected with more ambient air pollution. Exposure to pollutants can impair immune responses in people already at risk of developing morbidity after viral respiratory infections and may aggravate the health concerns of COVID-19 (Katoto et al., 2021). One meta-analysis found increased rates of COVID-19 infections and deaths in highly polluted areas, as well as a potential link between air pollution and an increase of airborne transmission of COVID-19 depending on meteorological factors (Ali et al., 2021).

Pittsburgh's air pollution is associated with industry and regional transportation from the Ohio River valley and the Monongahela River valley. The American Lung Association (2022) estimates that three out of every eight Americans live in high ozone smog areas with Allegheny County being one those areas. Daily fluctuations of ambient pollutants are significantly associated with hospital rates for congestive heart failure (Wellenius et al. 2005). Childhood asthma rates are also greater in Allegheny County compared to nationwide rates with socioeconomics playing a role in disparities (ACHD, 2019).

Previous studies observed pollution lockdown trends by ground-based (Tanzer-Gruener et al, 2020, Lange et al, 2022, Berman and Ebisu, 2020), space-based (Burton et al., 2021), combination of ground- and space-based (Naeger and Murphy, 2020, Xia et al., 2021, Qu et al., 2021), and meta-analysis of published studies (Gkatzelis et al., 2021). All studies used similar lockdown periods from March-April 2020 and analyzed pre-lockdown. Berman and Ebisu (2020) found that NO_2 levels declined during lockdown using the EPA OpenAQ data and pollutants had larger shifts in concentrations in urban areas.

Tanzer-Gruener et al. (2020) and Lange et al. (2022) have studied air pollution in the PIttsburgh region. Both studies observed a connection between a reduction of NO_2 and traffic related $PM_{2.5}$. Lange et al. (2022) noted the greatest reduction in $PM_{2.5}$ is around the Clairton Coke Works (Liberty and Clairton monitoring site). Tanzer-Gruener et al. (2020) observed similar reductions in the Pittsburgh area with a clear decrease in air pollution due to less vehicular traffic while $PM_{2.5}$ followed similar trends. However, neither study observed SO_2 or O_3 and focused mainly on traffic emissions. Also, these studies did not go into details on how and if meteorological covariates are calculated into their result to replicate, but it is noted in both studies that meteorological factors can influence pollutant concentration. As the pandemic is evolving, no studies previously mentioned had observations beyond the initial lockdown period of 2020.

2. DATA AND METHODS

In this study, the impact of stay-at-home orders (herein, lockdown) on localized and regional air pollution trends in the Pittsburgh (Allegheny County, Pennsylvania) region are examined using ground- and space-based monitoring.

2.1 Location and timeframes

Using the Environmental Protection Agency's (EPA) Interactive Map of Air Quality Monitors and the Allegheny County Health Department (ACHD), four stations were chosen to represent different socioeconomic areas of the Greater Pittsburgh Metropolis (Figure 1, Table A1).

To observe the city of Pittsburgh, the Lawrenceville monitoring station (43-003-0008) was chosen. According to the EPA, Lawrenceville is an NCore Monitoring Network Site, which is "...a multi pollutant network that integrates several advanced measurement systems for particles, pollutant gases, and meteorology" (EPA, 2022). This station is population-based community oriented in an urban district downwind from the Central Business District. The most significant sources of pollution for Lawrenceville are vehicular emissions and light industry. As an NCore site, the monitor can observe all criteria gases and particulate matter; however, it does not observe NO_2 but total reactive nitrogen (NO_y) when necessary.

To examine the industrial emissions, the Liberty monitoring station (42-003-0064) was chosen. This site is important to understand how pollutants affect blue-collar people living in the surrounding area. This suburban station is situated at a slightly higher elevation and downwind from the main pollutant source in the valley: the US Steel Clairton Coke Works. Liberty has higher than average levels of particulate matter and SO_2 and is located along the river with valleys and rolling terrain that has the capability to trap pollutants.

To observe regional transportation of pollutants, the South Fayette monitoring station (42-003-0067) was chosen. This is a suburban

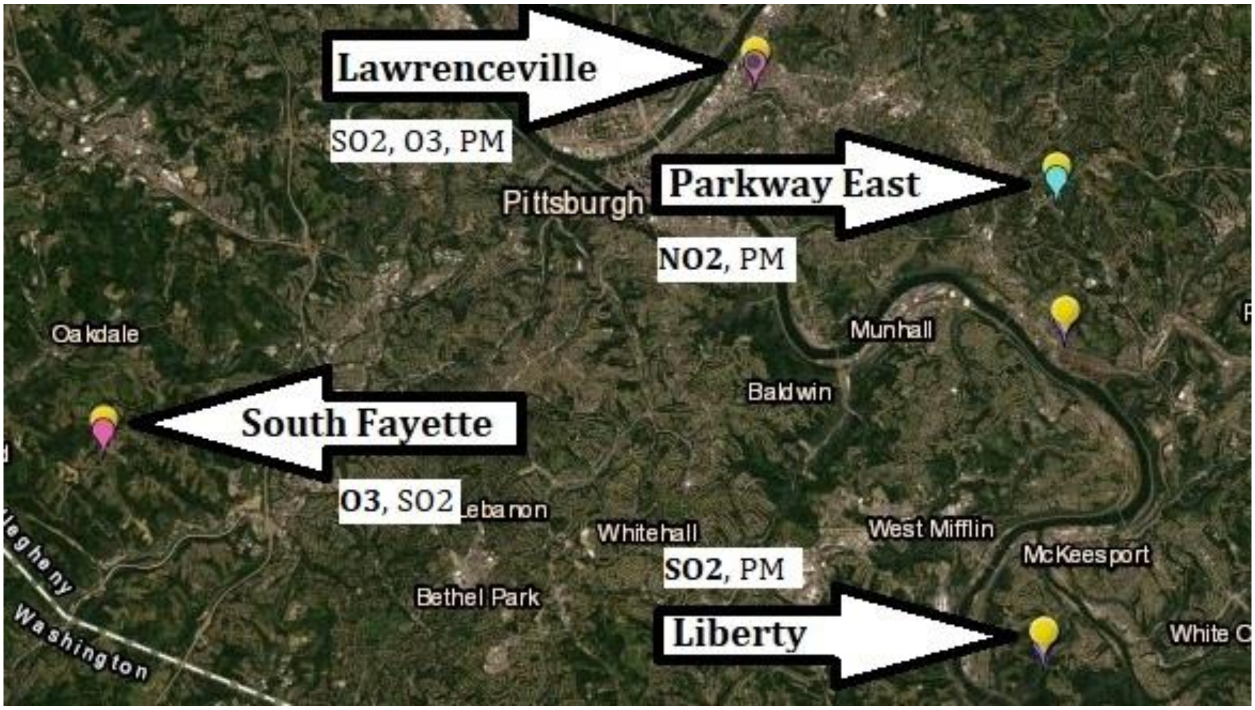

FIG 1. Map of the Greater Pittsburgh Metropolis with four station monitors and the main pollutant observed at each location, EPA 2022 with author modifications.

population-based location that has rolling terrain. According to the ACHD (2019), this site might reflect higher ozone concentrations partially due to the regional transport of criteria gases from the Ohio River valley industry. It is also suggested that the topographical elevation might have fluctuations in overnight ozone because of stratospheric intrusion (ACHD, 2019).

To observe vehicular emissions, the Parkway East monitoring station (42-003-1376) was chosen. The Parkway East (Interstate 376) is a major roadway that traverses into Pittsburgh from the east. It has an annual average daily traffic of approximately 76,000 vehicles (ACHD, 2019). This station measures the population exposure to roadway emissions. NO_2 emissions are at a microscale and the highest concentration in the Greater Pittsburgh Metropolis at this location. The Parkway East monitor is in a residential district with rolling terrain.

This study examines several factors for the lockdown timeframe by using Allegheny County to represent the Greater Pittsburgh Metropolis. On 16 March 2020, Pennsylvanian schools were closed, and bars and restaurants in Allegheny County ceased dine-in operations. On 19 March 2020, all non-life-sustaining businesses in Pennsylvania were closed to help mitigate the spread of COVID-19. On 23 March 2020, Allegheny County went into stay-at-home orders while 1 April saw statewide stay-at-home orders. As part of the reopening plan, Pennsylvania lessened restrictions through a three-phase plan depending on COVID-19 rates, public health indicators, and economic conditions (Commonwealth of Pennsylvania, 2020a). On 15 May 2020, Allegheny County was moved from the red stage to yellow stage. In the yellow stage, some businesses were able to reopen while restaurants and bars moved to outdoor dining. Therefore, the lockdown timeframe for this study began on 16 March 2020 until 14 March 2020.

2.2 Data – Ground- and space- based

The Environmental Protection Agency via the Clean Air Act monitors six criteria pollutants in the United States. For this study, only particulate matter less than 2.5 μm ($PM_{2.5}$), ozone, nitrogen dioxide, and sulfur dioxide are observed for lockdown pollution trends in the Greater Pittsburgh Metropolis area as defined by the Allegheny County Health Department (ACHD, 2019). $PM_{2.5}$ are solid and liquid matters suspended in the atmosphere, with an aerodynamic diameter less than 2.5 μm. Nitrogen dioxide (NO_2) and $PM_{2.5}$ are

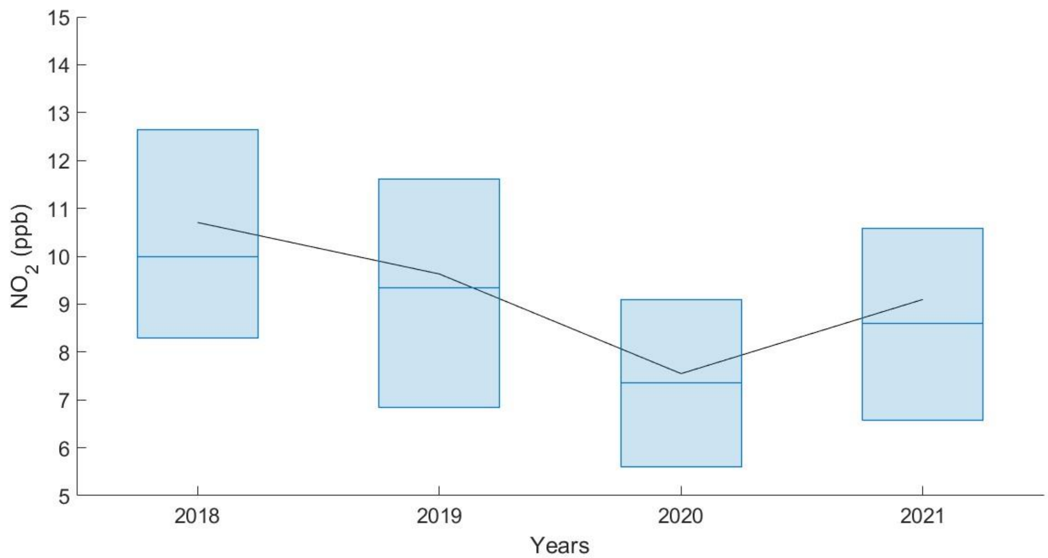

FIG 2. A box-whisker plot summarizing Nitrogen Dioxide (ppb) concentrations from the EPA between 16 March and 15 May during 2018-2021 over Parkway East. The yearly means are connected by the black line and the boxes represent the 25th, 50th (median), and the 75th percentiles of the concentrations for individual years.

predominantly produced through vehicular emissions, although $PM_{2.5}$ can also be released into the atmosphere as primary pollutants at source-points such as industrial sites and secondary pollutants from chemical reactions. Tropospheric ozone (O_3) is produced photochemically by the mixing of nitrogen oxides, volatile organic compounds, and sunlight. Ozone is normally stronger during warm sunnier days. Sulfur dioxide (SO_2) is also observed at the source-point in this study, however SO_2 is often transported by the southwestern wind into Allegheny County. Meteorological data of temperature, relative humidity, wind speed and direction, and pressure from the Lawrenceville NCore site was also collected. Each dataset had temperature recording; however, the Lawrenceville meteorological data was used for any necessary comparisons. To establish trends, data from 2018 through 2021 was used to reflect a pre-, during, and post-lockdown period. In this study, hourly data was used to calculate daily averages over the lockdown timeframe of all four years. Yearly mean and distribution percentiles are also calculated while disregarding outliers. Yearly mean data is provided in Appendix A, Table A2.

For the space-based datasets, this study uses data from the Tropospheric Monitoring Instrument (TROPOMI) from the European Space Agency Sentinel-5P sun synchronous satellite. TROPOMI uses a push broom imaging configuration with a swath of 2600 km and a high spatial resolution of 5.5 km by 3.5 km at nadir. The Sentinel has a daily equatorial overpass time of 13:30 local time. Using space-based data, it is possible to observe pollutants in places that may not be feasible for ground based, for example remote environments and over bodies of water. TROPOMI data can be used to observe pollutant transport and emission trends as it captures pollutant gases in the total atmospheric column over larger spatial scales. Total column of NO_2 and SO_2 are observed for the years of 2019 through 2021 using raw unaltered Level 2 offline datasets. The daily snapshots TROPOMI data are aggregated to obtain yearly mean and distribution percentiles, disregarding outliers. Data that did not pass quality assurance was also disregarded.

3. RESULTS AND DISCUSSION

3.1 Nitrogen Dioxide - EPA and TROPOMI

While pre-COVID-19 trends show a reduction in NO_2, a steep decline in 2020 is observed due to the lockdown impact on local traffic (Figure 2). NO_2 levels returned to pre-COVID-19 levels in 2021, suggesting anthropogenic NO_2 traffic emissions during COVID-19 lockdown were minimal. As only the Parkway East monitors for NO_2 emissions, it is speculated that all of Allegheny County would see

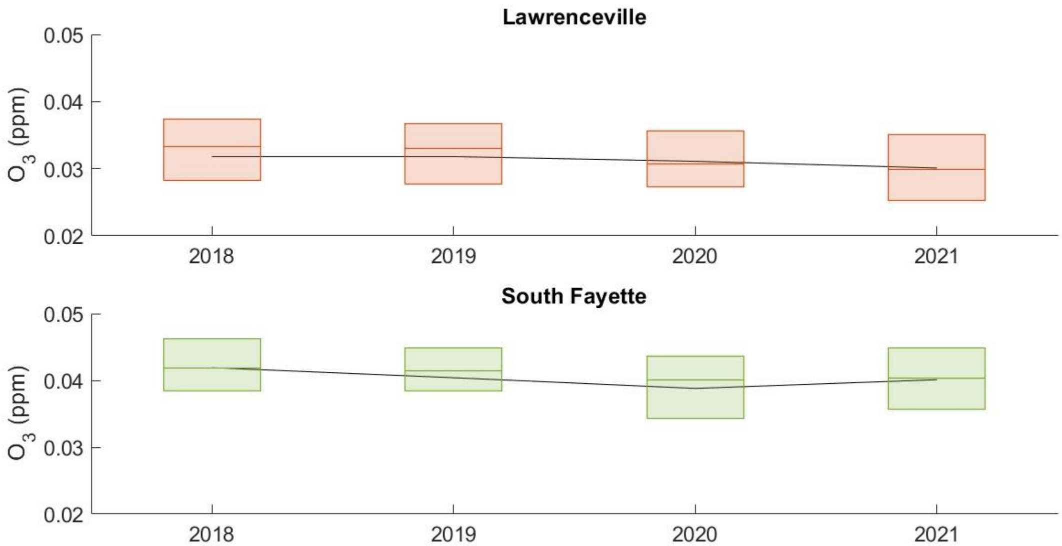

FIG 3. Ozone (ppm) concentrations from the EPA between 16 March and 15 May during 2018-2021 over South Fayette and Lawrenceville.

a similar impact. TROPOMI data reflects comparable trends in pre-COVID-19 reductions and post-COVID return levels (Figure A3).

Note that EPA data is ground-based observation reflecting the pollutants concentration on the surface while the TROPOMI data measures the entire atmospheric column. The TROPOMI raw data does not separate between the source and transport background NO_2. Transport background NO_2 can be natural emissions like wildfires or long-range pollutant emissions that have temporal fluctuations (Qu et al., 2021). TROPOMI's coarser spatial resolution takes a larger surface area into account unlike the Parkway East monitoring site that observes the ambient area near the EPA monitor. Response of satellite observations to changes in emissions is muted areas with weaker surface NO_2 emissions (Qu et al., 2021), and this may be the case within Allegheny County.

3.2 Ozone – EPA

The reduction of nitrogen dioxide would theoretically have an impact on ozone since the formation of tropospheric O_3 would require NO_x. A reduction in O_3 at both the South Fayette and Lawrenceville sites is observed (Figure 3). South Fayette is at a higher elevation and shows a larger difference partially due to a reduction of regional transport of NO_2 with levels rebounding to pre-COVID-19. Lawrenceville sits closer to the Allegheny River valley at a lower elevation thus would not have as strong a transport effect. Although the 2020 lockdown reduction in Lawrenceville is small compared to South Fayette, it also shows a steady scaling down of O_3 post-COVID-19. However, neither location has localized data for NO_2.

3.3 Sulfur Dioxide - EPA and TROPOMI

Three locations (South Fayette, Lawrenceville, and Liberty) convey a reduction of sulfur dioxide. Pre-COVID-19 rates at South Fayette and Lawrenceville (Figure 4) are very minimal, which can be assumed that SO_2 at those monitoring sites are due to localized and regional transports as there is only light industry at Lawrenceville. SO_2 levels in Liberty (Figure 4) show a steady decline into 2020 increasing to pre-COVID levels in 2021. Analyzing the TROPOMI satellite data (Figure A4), similar trends to Liberty are observed. TROPOMI data would show source-based and background SO_2, which is transported from the Ohio and Monongahela River valleys.

A major factor that influences SO_2 emission rates during COVID-19 lockdown in the Greater Pittsburgh Metropolis is industrial manufacturing. Allegheny County has active steel and coke manufacturing that was considered an essential business (Commonwealth of Pennsylvania, 2020b). This depends upon high

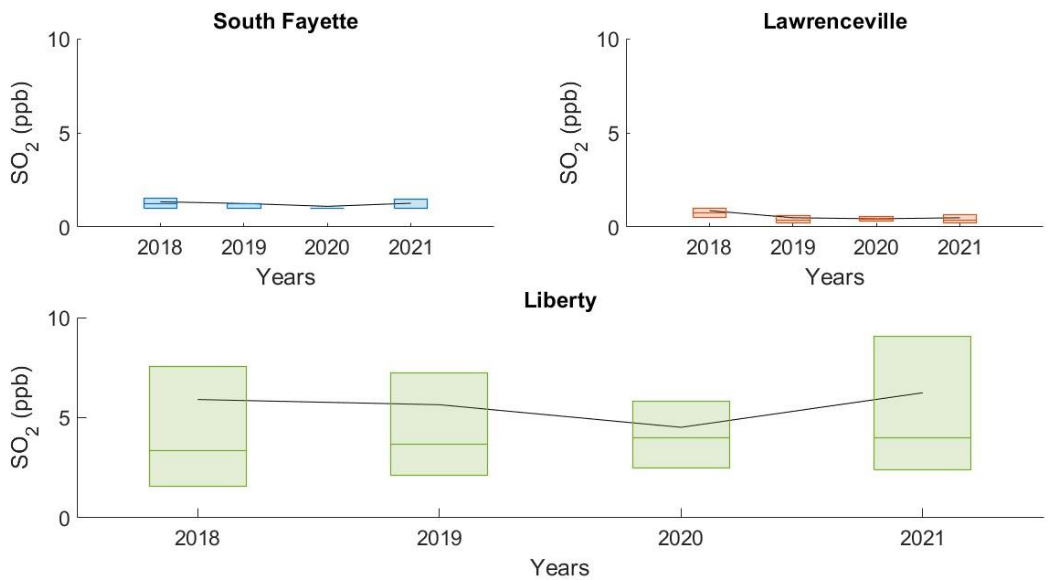

FIG 4. Sulfur Dioxide (ppb) concentrations from the EPA between 16 March and 15 May during 2018-2021 over South Fayette, Lawrenceville, and Liberty.

amounts of fuel to maintain the blast furnaces, which normally run 24-hours 7-days a week as it requires too much energy to cool and reheat. Even with a sluggish steel industry, furnaces are still active, constantly releasing varied levels of pollutants into the air. Unless the Clairton Coke Works permanently closes, SO_2 levels at Liberty will always need monitoring.

3.4 Particulate Matter 2.5 – EPA

A consequence of traffic and industry is particulate matter. Three locations (Parkway East, Lawrenceville, and Liberty) display a reduction during the 2020 lockdown in $PM_{2.5}$ (Figure 5). High concentration days of $PM_{2.5}$ are dominated by secondary sources (chemical reactions from NO_2 and SO_2). With lesson emissions of both pollutant gases, it is speculated that $PM_{2.5}$ from those

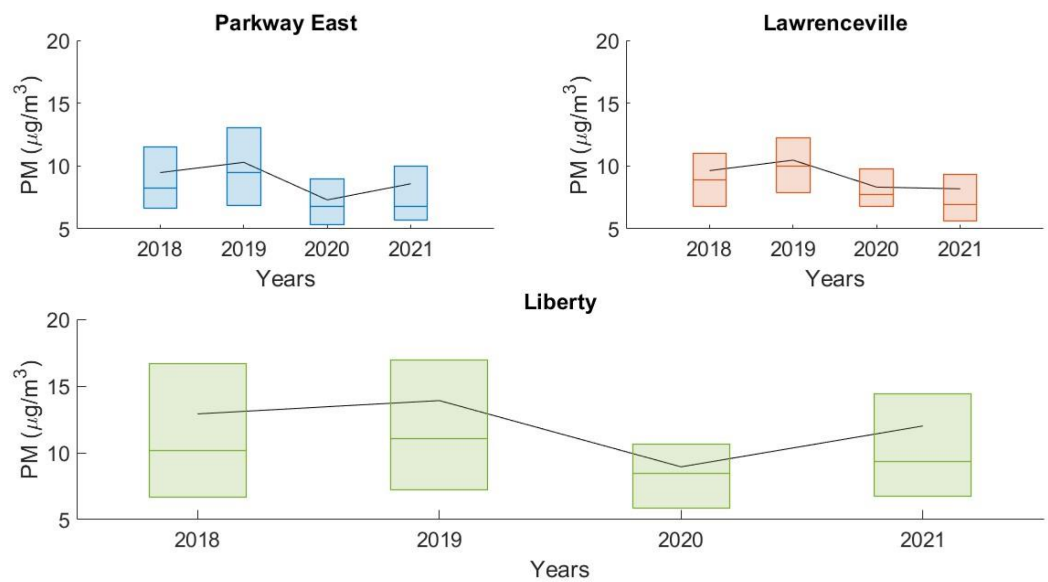

FIG 5. Particulate Matter 2.5 from the EPA between 16 March and 15 May during 2018-2021 over Parkway East, Lawrenceville, and Liberty.

sources would also be reduced. This is shown at the Parkway East (NO_2) and Liberty (SO_2) stations. Less demand of steel during the lockdown period could have played a role in a reduction of primary source $PM_{2.5}$ at Liberty. Lawrenceville also saw a reduction of $PM_{2.5}$ since it is affected by the regional flow of $PM_{2.5}$ along with source-based from roadways. As the Central Business District had less activity during the 2020 lockdown, there was less traffic in and around Lawrenceville.

3.5 Meteorological Factors

We compare meteorological factors of temperature, relative humidity, wind speed and direction, and pressure to pollutants at various locations. For most species and conditions, no inference can be made beyond what is known with pollution transport and wind. Figure 6 shows the relationship between temperature and ozone in South Fayette. There is a connection between high temperatures and ozone formation as stronger solar radiation aids in the photochemical process. There is a small trend in the data that reflects this; however, it is not a strong relationship. One speculation may be that lockdown temperature averages may not have been strong enough to make a difference. ACHD (2019) has noted that South Fayette could experience overnight stratospheric intrusion of O_3 which could have also skewed the data. As this study uses daily averages, more research would be needed to observe if this is the case and to be able to separate between photochemical and intrusion.

Meteorological influences have been shown to influence NO_2 columns by an average of 12% from 2019 to 2020 (Qu et al., 2021), which may require modifications to reflect the importance of seasonal and annual variants on pollution transport. One important factor is the wind. Pittsburgh's prevailing winds are from the southwest, bringing pollutants from the coal fired power plants from the Ohio River valley. Wind speed at Liberty was analyzed, but no conclusive relationships can be made between stronger emissions with less wind speed (Figure A5) at this location. This could be attributed to discrepancies with the meteorological data and the elevation of the station relevant to the river valley and smokestacks of the Clairton Coke Works.

Lawrenceville is the only station we observed that has meteorological data beyond temperature via the EPA. Because of the topographical nature of Pittsburgh and Allegheny County, there are no universal options to best observe individual factors at any given station. Lawrenceville is in the Allegheny River valley, and this elevation difference could cause noticeable discrepancies in weather compared to Liberty or South Fayette. The National Weather Service and

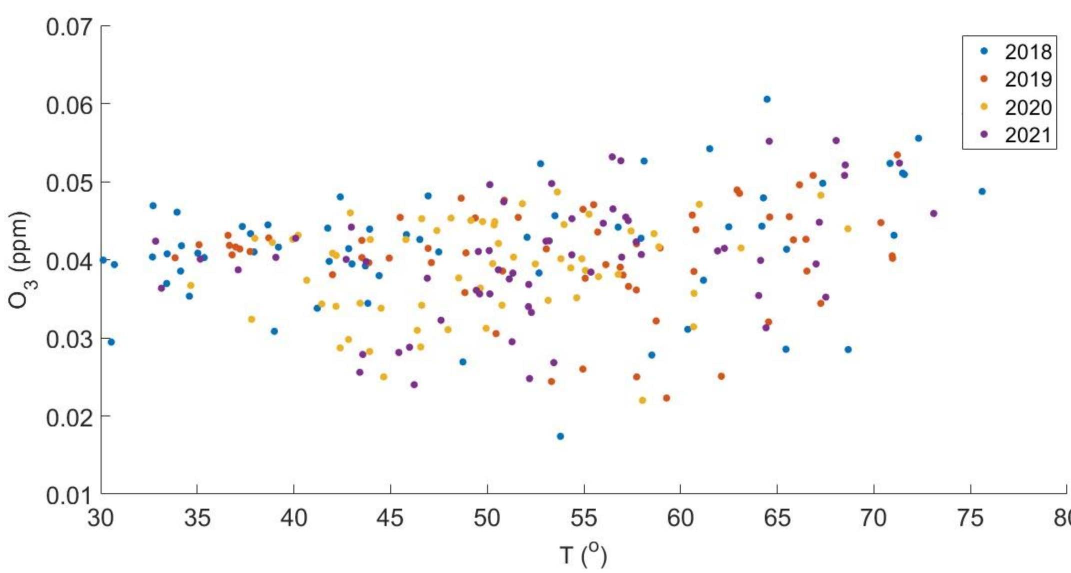

FIG 6. Relationship between temperature (Fahrenheit) and ozone (ppm) at South Fayette from the EPA between 16 March and 15 May during 2018-2021.

local county airports could provide additional data for comparisons to the Lawrenceville data along with soundings to establish inversions.

3.5.1 Inversions

Tanzer-Gruener et al. (2020) explored the boundary layer's impact on overnight emissions which can correspond to surface temperature inversion. The worst-case air pollution in Allegheny County is often accompanied by inversions. The mixing of the atmosphere is suppressed, and pollutants released into the air can strengthen in concentration near the surface. In many of the valleys and low-lying areas, inversions can easily form, and be more persistent and intense compared to elevated areas. Inversions form soon after sunset and last until a few hours after sunrise, and in rare cases conditions extending beyond 24-hours have occurred. These conditions are due to stagnant periods of high-pressure systems as what was experienced with the Donora Smog of 1948. Subramanian et al. (2007) suggested that contributions of coke-oven emissions are higher during inversion days. This is important in Liberty, which is strongly influenced by the meteorological conditions that cause inversions. It was not feasible to observe inversions within this study as it would require more understanding of the boundary layer and may not have a strong adverse effect on emissions in 2020. However, it is important to note that inversions do occur in the Pittsburgh area and might influence pollutant concentrations.

3.6 TROPOMI limitations

TROPOMI has its limitations compared to ground-based observations. For example, it requires minimal cloud coverage, and the concentrations of pollutants can vary due to local and regional transportation. Burton et al. (2020) noted that there is significantly coarser spatial resolution and sensitivity at the edge of the swath. Naeger and Murphy (2020) used both ground-based and the TROPOMI satellite data to observe a reduction of pollutants. They noted that winds can impact the NO_2 column space-based measurements, creating false values of cleaner air than observed with ground-based monitoring (2020). Xia et al. (2021) also found less emissions at the source-point with the ability of the TROPOMI detecting SO_2 pollution at industrial hot spots. Qu et al. (2021) noted satellite observations can capture the magnitude of nitrogen oxides emission reductions only from sites with the highest level of surface NO_2 when compared to ground-based EPA data. Large scale synoptic systems have been shown to increase 12% by average in NO_2 columns from 2019 to 2020 (Qu et al., 2021), thus the importance of transport can change seasonally and annually.

4. CONCLUSION

We examined SO_2, NO_2, O_3, and $PM_{2.5}$ using the EPA ground-based and satellite data sets in the Greater Pittsburgh Metropolis during 2018 - 2021 to assess the impact of COVID-19 lockdowns on the anthropogenic emission trends. The lockdown took place between 16 March 2020 to 15 May 2020, so we compared the annual pollutant emissions over the same dates of the year in those four years. We found that most of the pollutant emissions explored stemmed from anthropogenic sources as pollutants in most locations returned to pre-COVID-19 levels a year after the lockdown. It can be speculated that with the local- and state-wide lockdowns of 2020, there has been a reduction of criteria gases and particulate matter within that time frame, which is consistent with the findings by Tanzer-Gruener et al. (2020) and Lange et al. (2022). Using space- and ground-based data, governmental agencies can continue to monitor pollution trends and transport. It has been suggested in previous studies that meteorological factors may play a role in COVID-19 transmission, and careful observation in worldwide pollution could offer solutions on how to adjust to an evolving virus.

Gkatzelis et al. (2021) notes several inconsistencies and improvements for future research in their meta-analysis: the need for accounting for annual variability of meteorology, combining space-based data with high quality weather analysis and chemical modeling as satellite retrievals alone suffer from uncertainties, and careful comparisons of meteorological normalized ozone and photochemical ozone models for mitigation strategies.

With better understanding of emission trends, it is possible to advocate for better environmental policies in the industry and energy sector to help mitigate emissions. Continuing research can be used to demonstrate how the reduction of human activities can greatly improve air quality and human health. Two meta-analyses

(Ali et al. (2021) and Katato et al. (2021)) of COVID-19 infections rates and air pollution show a potential correlation. Societal shifts in human activities and stay-at-home efforts can impact the future short-term and long-term air quality. Measures like remote and hybrid work environments, reducing unnecessary travel, better technologies and renewable energy resources in industry, and improving vehicle emissions are just some ways pollution can be minimized.

5. ACKNOWLEDGEMENTS

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6. DATA AVAILABILITY

The raw hourly criteria gases, particulate matter, and meteorological data are downloaded from the EPA AirData website: https://aqs.epa.gov/aqsweb/airdata/download_files.html#Raw (access 21 June 2020).The EPA Interactive Map of Air Quality is found here: https://www.epa.gov/outdoor-air-quality-data/interactive-map-air-quality-monitors (access 21 June 2020). The TROPOMI NO_2 and SO_2 data are downloaded from http://www.tropomi.eu/data-products/nitrogen-dioxide and http://www.tropomi.eu/data-products/sulphur-dioxide (access 14 July 2020).

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APPENDIX A
Supplemental Information

TABLE A1. Station number, latitude and longitude coordinates, species

Location	Station Number	Latitude	Longitude	Species
Lawrenceville	42-003-0008	40.465420	-79.960757	O_3, SO_2, PM2.5
Liberty	42-003-0064	40.323768	-79.868062	SO_2, PM2.5
South Fayette	42-003-0067	40.375644	-80.169943	O_3, PM2.5
Parkway East	42-003-1376	40.437430	-79.863572	NO_2, PM2.5

TABLE A2. Yearly mean by location, species, and year

Location	Species	2018	2019	2020	2021
Parkway East	NO_2 (ppb)	10.7054	9.6294	7.5484	9.0978
Lawrenceville	O_3 (ppm)	0.0318	0.0318	0.0311	0.0301
South Fayette	O_3 (ppm)	0.0491	0.0404	0.0388	0.0401
Lawrenceville	SO_2 (ppb)	0.8683	0.4963	0.4386	0.4925
Liberty	SO_2 (ppb)	5.9084	5.6467	4.5193	6.2431
South Fayette	SO_2 (ppb)	1.3389	1.2491	1.0981	1.2619
Lawrenceville	$PM_{2.5}$ ($\mu g\ m^{-3}$)	9.6313	10.4647	8.3197	8.1828
Liberty	$PM_{2.5}$ ($\mu g\ m^{-3}$)	12.9158	13.9116	8.9493	12.0097
Parkway East	$PM_{2.5}$ ($\mu g\ m^{-3}$)	9.4741	10.2894	7.2989	8.5871

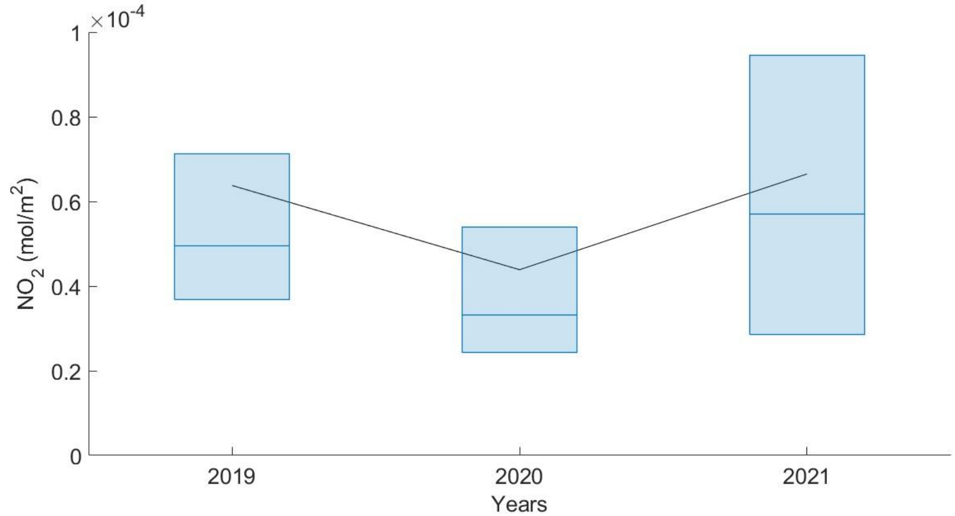

FIG A3. A box-whisker plot summarizing Nitrogen Dioxide (mol/m^2) concentrations from TROPOMI between 16 March and 15 May during 2019-2021. The yearly means are connected by the black line and the boxes represent the 25th, 50th (median), and the 75th percentiles of the concentrations for individual years.

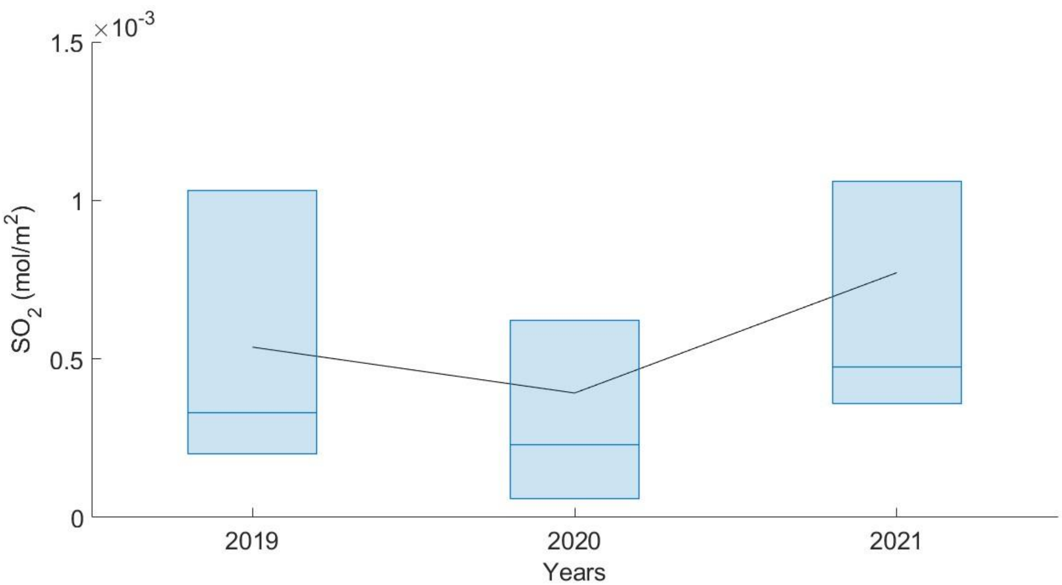

FIG A4. A box-whisker plot summarizing Sulfur Dioxide (mol/m2) concentrations from TROPOMI between 16 March and 15 May during 2019-2021.

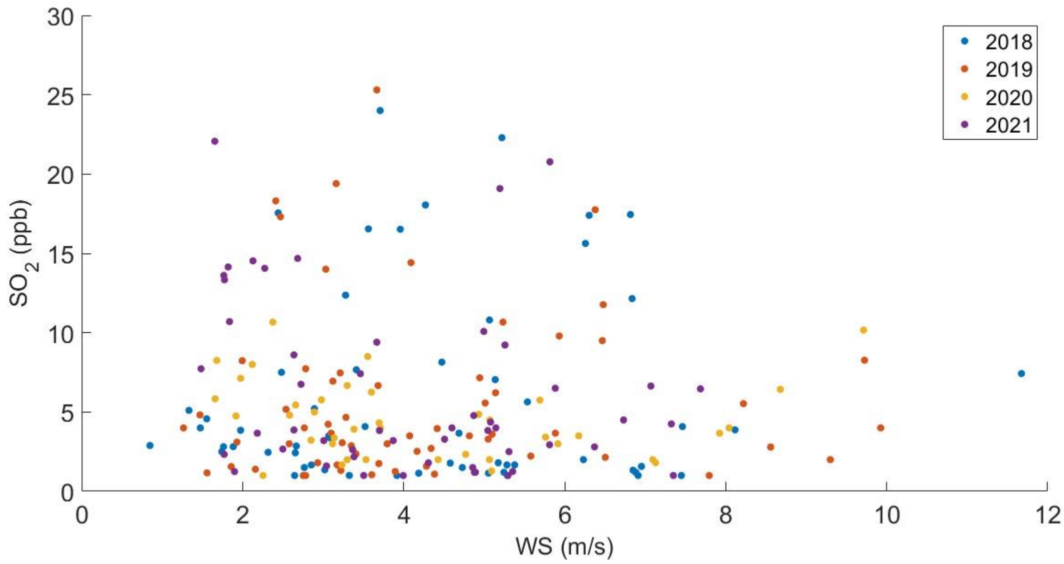

FIG A5. Relationship between wind speed (m s^{-1}) and sulfur dioxide (ppb) at Liberty from the EPA between 16 March and 15 May during 2018-2021.