Temporal trends in ambient fine particulate matter air pollution in Grenada, West Indies in 2020

by

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Abstract

Routine collection of ambient air quality data is rare in the Caribbean. To assess the potential for health impacts from exposure to ambient fine particulate matter ($PM_{2.5}$), an exposure study in Grenada was conducted. This study looked to characterize temporal trends of $PM_{2.5}$ and changes in the concentrations of this pollutant during dust storms. Four fixed-site stationary monitors were installed in Grenada and one on neighbouring island of Carriacou. They continuously captured $PM_{2.5}$ concentrations between January 6 and October 31, 2020. Regression analyses were performed to describe associations between ambient $PM_{2.5}$ and meteorological variables. Daily mean $PM_{2.5}$ concentrations were approximately 2.5 times higher on Saharan dust days than non-Saharan dust days (8.9 vs 3.6 $\mu g/m^3$; $p<0.05$). Concentrations measured during the June 2020 Saharan dust storm exceeded the World Health Organization's 24-hour guideline. While concentrations of $PM_{2.5}$ are low in Grenada relative to other countries, they still pose a health hazard.

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List of Abbreviations

Abbreviation	Description
AOD	Aerosol Optical Depth
AOT	Aerosol Optical Thickness
AOT_{470}	Aerosol Optical Thickness in the blue band
CO	Carbon Monoxide
COPD	Chronic Obstructive Pulmonary Disease
COVID-19	Coronavirus Disease 2019
CVD	Cardiovascular Disease
GDP	Gross Domestic Product
HO_2	Hydroperoxyl Radicals
H_2O_2	Hydrogen Peroxide
HF	Heart Failure
IARC	International Agency for Research on Cancer
IHD	Ischemic Heart Disease
IL	Interleukin
IQR	Interquartile Range
LUR	Land Use Regression
MERRA-2	Modern-Era Retrospective Analysis for Research and Applications Version 2
MI	Myocardial Infarction
NAAPS	Navy Aerosol Analysis and Prediction System
NADD	North African Desert Dust

NH_3	Ammonia
NO	Nitrogen Oxide
NO_2	Nitrogen Dioxide
NO_X	Nitrogen Oxides
O_2	Dioxygen
O_2^-	Superoxide Ion
O_3	Ground-level Ozone
OH^-	Hydroxide Ion
OR	Odds Ratio
PAH	Polycyclic Aromatic Hydrocarbon
PM	Particulate Matter
$PM_{0.1}$	Particulate Matter with particles of aerodynamic diameter < 0.1 µm
$PM_{2.5}$	Particulate Matter with particles of aerodynamic diameter < 2.5 µm
PM_{10}	Particulate Matter with particles of aerodynamic diameter < 10 µm
ROS	Reactive Oxygen Species
RR	Risk Ratio
SARS-CoV-2	Severe Acute Respiratory Syndrome Coronavirus 2
SO_2	Sulphur Dioxide
SO_X	Sulphur Oxides
VOC	Volatile Organic Compound
WHO	World Health Organization

1. Introduction

Ambient air pollution is a major environmental-related health risk factor for cardiovascular, cerebrovascular, and respiratory diseases.[1–3] The International Agency for Research on Cancer has also classified ambient air pollution and particulate matter (PM) air pollution as a human carcinogen.[4] Health effects associated with air pollution may result from either acute (i.e., day to day changes) or chronic (i.e., over a long period of time) exposures. The Global Burden of Disease Study estimated that worldwide, in 2017, ambient particulate matter air pollution caused 2.94 million deaths and 83 million disability adjusted life years (i.e., years of "healthy" life lost).[2] Subgroups of the populations most vulnerable to air pollution include newborns, children, elderly people, individuals with pre-existing cardiovascular and respiratory diseases, and individuals with specific genetic polymorphisms.[3,5] Given the many potential sources of ambient air pollution, its ubiquity, and health impacts, air pollution monitoring is necessary to effectively guide air pollution management and mitigate its health impacts.

Situated in the West Indies, the island nation of Grenada has an estimated population of 113,094 people (as of July 2021). To date, Grenada has not had a program to continuously monitor ambient air pollution.[6] Also known as the "Spice Island", Grenada has a mostly tropical climate tempered by the north easterly trade winds. Grenada's air quality differs from most other nations because of the diversity of air pollution sources that include use of fossil fuels for the generation of electricity, motor vehicles, ocean-going vessels, as well as open waste burning, and local industry.

In addition to the above sources of air pollution, Grenada, like other islands in the Caribbean, has been impacted by North African desert dust (NADD) episodes. In June

2020, the Caribbean experienced its largest such NADD storm in the last 50 years.[7] These storms, which typically last for 3-4 days, are thought to pose health risks due to temporary increases in ambient concentrations of particulate matter.[8] In the event of upcoming NADD storms, the Health Ministry of Grenada issues public health advisories and recommendations to reduce exposure during these periods of diminished air quality. NADD include particles such as mineral dust,[9] biological (plant detritus, pollen, bacteria, viruses, fungal spores)[10] and other chemical (pesticides, herbicides, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls, industrial emissions)[10,11] components.

This project was motivated by the lack of a continuous systematic monitoring program of ambient air pollution in Grenada. The primary goal of this project was to characterize temporal changes in ambient concentrations of particulate matter air pollution, and assess how these concentrations changed during NADD events. These objectives also accounted for the role of other meteorological factors such as temperature, visibility, wind speed, relative humidity, precipitation, and atmospheric pressure. This characterization of the temporal changes in air pollution is a necessary first step to better understand how air quality impacts the health of Grenadians.

Importantly, the monitoring of ambient particulate matter air pollution for this project started in January 2020, immediately preceding the emergence of the worldwide coronavirus disease (COVID-19) pandemic. Many countries have reported reduced levels of air pollution that have been attributed to public health practices put in place to reduce person to person spread of COVID-19.[12] Grenada was similarly impacted by COVID-19 and implemented several such public health measures that included physical distancing policies, travel restrictions, and curfews. The air pollution monitoring data that were collected in Grenada provided the opportunity to assess the extent to which public health policies, designed to reduce transmission of COVID-19, lowered concentrations of $PM_{2.5}$.

This thesis is structured to first include abridged reviews on the human health effects from exposure to air pollution, previous studies of desert dust episodes, as well as NADD episodes in the Caribbean. The review also summarizes findings from studies that examined the impacts of COVID-19 on air quality. This review is followed by providing a study rationale and statement of research objectives. Following this literature review, a rationale and statement of research objectives for this thesis is provided. This is then followed by the methods, and the presentation and the interpretation of the study findings.

2. Literature Review

2.1. Air Pollution and Human Health

Air pollution is a ubiquitous environmental exposure that adversely affects human health. In 2017, an estimated 4.9 million deaths worldwide resulted from air pollution.[2] Cardiovascular, cerebrovascular, and respiratory disease mortality account for a large portion of these deaths caused by air pollution.[2] In addition to mortality impacts, chronic exposure to low levels of air pollution has substantial impacts on morbidity. This is indicated by the estimated 143 million disability adjusted life years (i.e., years of "healthy" life lost) that occurred globally in 2017, due to air pollution.[2] In this section, criteria air pollutants that are monitored and regulated by Health Canada are discussed, health effects of air pollution are summarized, and various approaches used to measure air pollution are described.

2.1.1. Criteria Pollutants

Criteria air pollutants refer to those that are monitored and regulated to reduce human health impacts. Health Canada has identified seven criteria air pollutants: sulphur oxides (SO_X), nitrogen oxides (NO_X), volatile organic compounds (VOCs), PM, carbon monoxide (CO), ammonia (NH_3), and ground-level ozone (O_3).[13] There are two broad categories of air pollutants: 1) gaseous pollutants such as sulphur and nitrogen oxides and 2) particulate pollution. Particulate matter pollution is usually measured by mass and classified by aerodynamic diameter of the particles. Common types of particulate matter pollution include coarse particulate matter (particles with an aerodynamic (or mass median) diameter of < 10 μm; PM_{10}), fine particulate matter (particles with an aerodynamic diameter of < 2.5 μm; $PM_{2.5}$), and ultrafine particulate matter (particles with an aerodynamic diameter of < 0.1 μm; $PM_{0.1}$). The figure below provides a visualization of how these particles compare to each other according to size.

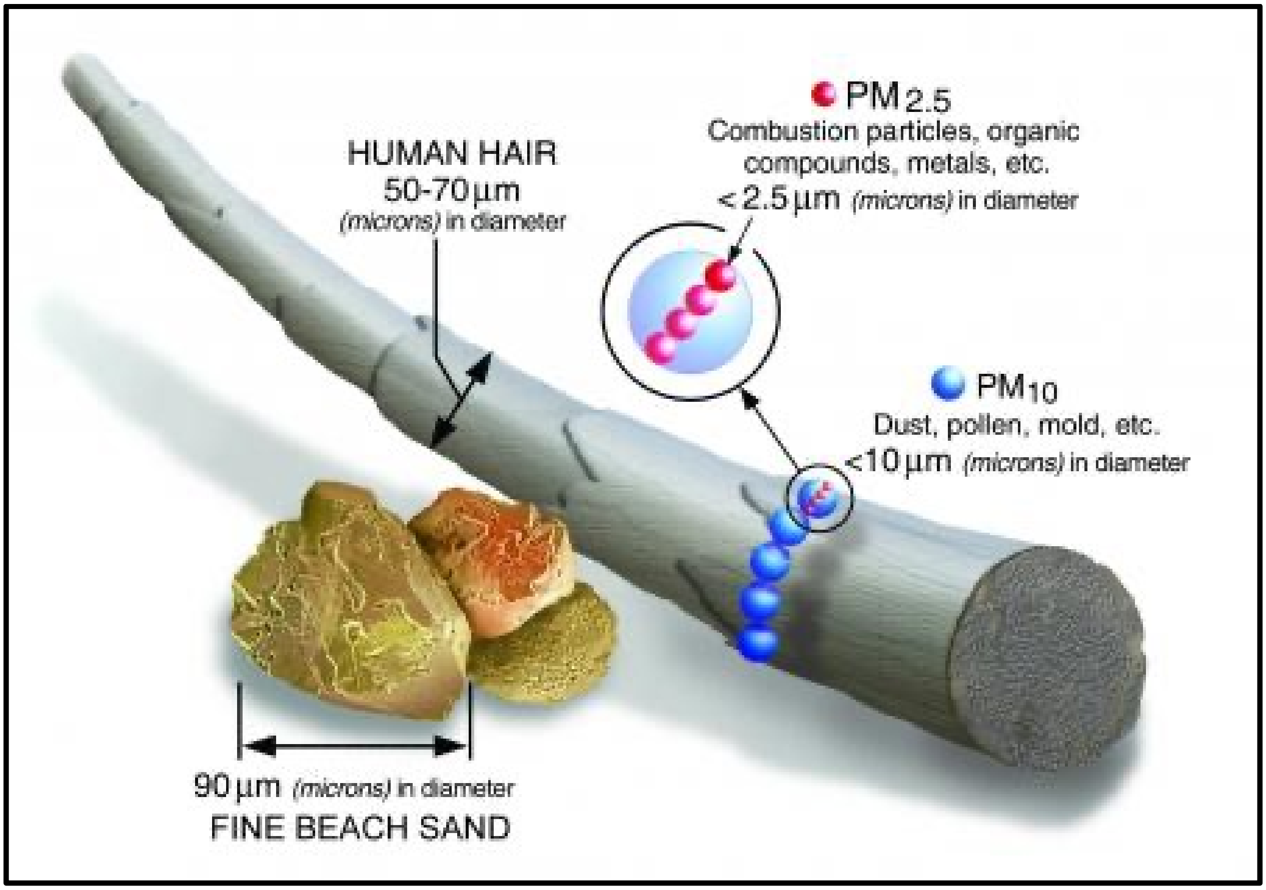

***Figure 1**: Comparison of particle size for different types of particulate matter air pollution (PM_{10}, $PM_{2.5}$, and $PM_{0.1}$).*[14]

Due to having a wide range of anthropogenic and natural sources, PM is found in all environments. Anthropogenic sources include solid-fuel (coal, lignite, heavy oil, and biomass) combustion, industrial and agricultural activities, erosion of pavement by automotive traffic, and the abrasion (the process of scraping or wearing away of materials) of vehicle brakes and tires.[15] Natural sources include volcanoes, dust storms, forest fires, sea-salt spray, and bioaerosols such as pollen and plant matter.[16] Particulate matter from combustion sources is usually smaller in particle size than those from material abrasion.[17] Due to having many potential sources, the composition of PM is highly variable by region.[18] Components such as transition metals, crustal material, polycyclic aromatic hydrocarbons, carbonaceous material, sulphates, nitrates, and biological matter can make up the particles themselves or be adsorbed on.[19,20]

During high temperature combustion, nitrogen oxides such as nitric oxide (NO) and nitrogen dioxide (NO_2) are emitted. The primary source of NO_2 is from fossil fuel combustion from automotive vehicles, with additional contributions from the generation of power, and other industrial sources. Nitrogen dioxide scavenges ground-level ozone, as through oxidation reactions NO and O_3 are converted to NO_2 and dioxygen (O_2).[20] Therefore, O_3 concentrations are inversely correlated with NO_2 and tend to be lower near large sources of fossil fuel combustion. Ambient CO is mainly emitted from the incomplete combustion of carbonaceous fuels (gasoline and natural gas) in automotive vehicles, and is highly correlated with NO_2.[21] Areas where ambient CO concentrations are highest include traffic canyons, road tunnels, and multi-story car parks, as they are microenvironments with low air circulation.[20]

Volatile organic compounds (VOCs) represent another criteria pollutant. They are emitted by the chemical and petrochemical industries and some building products. Examples of VOCs include toluene, benzene, ethylbenzene, and xylene.[22]

Of the family of sulphur oxide gases, sulphur dioxide (SO_2) is of greatest concern and the target of national ambient air quality standards in Canada.[23,24] Other sulphur oxide gases are found in the atmosphere (e.g., sulphur trioxide), albeit at lower concentrations than SO_2.[25] Ambient SO_2 is emitted from combustion and refining processes that involve sulphur containing materials such as coal, oil, and metal-containing ores.[26] While fossil fuel combustion continues around the world, outdoor emissions of SO_2 have been drastically reduced in recent history due to the increasing use of lower sulphur fuel and coal use.[20]

The seventh criteria air pollutant, ammonia (NH_3), is a colorless gas generated mostly from livestock, soil, or mobile emissions. When interacting with inorganic acids in the atmosphere, ammonia enhances the formation of secondary organic aerosols such as ammonium sulphates and ammonium nitrate.[27]

2.1.2. Impact of Local Meteorology on Ambient Particulate Matter Concentrations

Local meteorological factors such as temperature, relative humidity, wind speed, and precipitation impact ambient concentrations of PM. The impact of temperature on PM concentrations is highly variable, and is influenced by the composition of PM.[28] Precipitation typically decreases concentrations of PM,[28] due to the 'scavenging' effect of rain droplets. Precipitation washes out particulate matter from the atmosphere and dissolving gaseous pollutants.[29] An increase in ventilation (wind speed, mixing depth) typically results in decreased PM concentrations by a factor of 10 when replacing air in polluted regions with diluted background air.[28] Similarly, relative humidity has been found to have a negative association with ambient particulate matter in multiple locations, likely explained by the particulate absorption of water in higher humidity conditions which leads to particulate deposition.[30–33]

2.1.3. Health Effects of Air Pollution

Individuals exposed to air pollution are at a higher risk of several adverse health outcomes. Air pollution can increase these risks as a result of acute (short-term) or chronic (long-term) exposures. However, it is recognized that the increases in risk for all-cause and cardiopulmonary mortality from chronic exposure to air pollution far exceed those from short-term, or day-to-day increases.[34] Specifically, the risk coefficients from studies of longer exposure to air pollution tend to be higher than the corresponding risks from short-term exposure for the same health outcomes.[35] Moreover, longer-term exposures, unlike short-term exposures, are linked to outcomes such as cancer incidence, and dementia.[36,37] As the focus of this thesis is on particulate matter pollution, this section focuses on health effects associated with this pollutant. The following subsections will examine the effect of particle size, the associated biological mechanisms, and the impact of this pollutant on cardio-respiratory health, and cancer.

Characteristics of Particulate Pollution

Experimental studies have shown that the smaller the particle, the more easily it is able to penetrate deeper into the respiratory tract and impact health.[1] Specifically, when nasal-breathing, particles with an aerodynamic diameter greater than 10 μm are caught by cilia and mucus. Coarse particles, between 2.5 and 10 μg/m^3, usually settle quickly in the mouth, nose, upper throat, or primary bronchi. Most of these coarse particles are then discharged from the body as sputum or mucus via coughing or sneezing. Due to their larger size, coarse particles are thought to have less of an effect on human health when compared to finer particles ($PM_{2.5}$ or $PM_{0.1}$).[38] Particles between 1 and 5 μm in aerodynamic diameter are deposited mostly in the respiratory bronchioles and pulmonary alveoli where gas exchange occurs. Due to these smaller particles being able to affect gas exchange or even penetrate the lung, upon inhalation, they can severely hinder lung function.[1,38] Particles smaller than 1 μm in aerodynamic diameter can penetrate the pulmonary alveoli and escape into the bloodstream,[1] (either directly as naked particles or via endocytosis by alveolar macrophages or endothelial cells)[39–42] which can result in significant cardiovascular and cerebrovascular health outcomes.

Particulate matter composition also influences the extent to which exposure impacts health. Components that can be adsorbed (the coating of a thin film of gas, liquid, or solute molecules on the outer or internal surfaces of a material) onto PM can broadly be separated into biological and chemical categories.

Biological components of PM generally include plant pollen, viable or non-viable microorganisms (fungi, bacteria, viruses) as well as organic compounds that evolve from microbes (endotoxins, metabolites, toxins and other microbial fragments).[43] These components are of respirable size (0.015 to 0.3 μm for viruses, 0.2 to 5 μm for bacteria, 17 to 58 μm for plant pollens, and 1 to 30 μm for fungi).[44–47] They can be present in either coarse or fine fractions of particulate matter. Separate and synergistic effects from combined exposure to bioaerosols (tiny airborne particles that are biological in nature) and different components of PM can aggravate respiratory allergy and other pulmonary diseases.[48]

Chemical components of PM can include carbonaceous components such as organic carbon, elemental carbon, carbonate carbon, and also inorganic components such as crustal elements, trace metals, and ionic species.[49] Epidemiologic studies have identified that elemental carbon, organic carbon, and nitrates are associated with increased risks for cardiovascular and respiratory hospital admissions and mortality.[50–52] Exposure to elemental components of $PM_{2.5}$ such as Ni, Zn, Si, Al, V, Cr, As, and Br have also been shown to increase the risk of cardiovascular and respiratory hospital admissions and mortality.[50,53,54] Due to their bioavailability and redox properties, transition metals in PM are considered very important for their toxic effects and oxidative damage in the cardiopulmonary system.[55–57]

Ambient Particulate Matter Pollution and Respiratory Health

Epidemiological studies have consistently found that daily increases in particulate matter increase the risk of respiratory morbidity and mortality.[58–60] In a systematic review and meta-analysis of 26 studies of short-term exposures to air pollution and chronic obstructive pulmonary disease (COPD) and asthma in East Asia, researchers found statistically significant summary pooled risk ratio (RR) estimates for PM_{10} and $PM_{2.5}$.[58] Pooled RR estimates of 1.014 for all-type (i.e., general and emergency) COPD hospital admissions (all ages) and 1.013 for all-type asthma hospital admissions (all ages) were found in relation to a 10 μg/m^3 increase in PM_{10}. Pooled RR estimates of 1.022 for all-type COPD hospital admissions (all ages) and 1.013 for all-type asthma hospital admissions (all ages) were found in relation to a 10 μg/m^3 increase in $PM_{2.5}$. This review also examined the impact of these short-term exposures to air pollution on vulnerable groups such as children (≤ 14 years of age) and the elderly (≥ 65 of age). For the elderly, pooled RR estimates of 1.007 for all-type COPD hospital admissions and 1.010 for all-type asthma hospital admissions were found per 10 μg/m^3 increase in PM_{10}, and a pooled

RR estimate of 1.021 for all-type asthma hospital admissions was found per 10 μg/m^3 increase in $PM_{2.5}$. For children, pooled RR estimates of 1.021 and 1.022 for all-type asthma hospital admissions were found per 10 μg/m^3 increase in PM_{10} and $PM_{2.5}$, respectively.[58]

Another systematic review and meta-analysis examined short-term exposures to ambient $PM_{2.5}$ and hospitalizations and mortality from COPD. Based off the 18 (twelve for COPD hospitalizations and six for mortality from COPD) studies examined, a 10 μg/m^3 increase in $PM_{2.5}$ was associated with a 3.1% increase in COPD hospitalizations and 2.5% increase in mortality from COPD (lag days 0-7).[59] In a report of the estimated effects of ambient PM_{10} concentrations on respiratory mortality across 29 European cities within the "Air Pollution and Health: a European Approach Project", a 10 μg/m^3 increase in PM_{10} (lag days 0-1) was associated with a 0.58% increase in respiratory deaths.[60]

Recent epidemiological studies indicate that long-term exposures to particulate matter pollution is associated with increased respiratory morbidity and mortality.[61–63] In a systematic review and meta-analysis that examined the impacts of long-term exposures to ambient $PM_{2.5}$ and incidence of COPD, based on seven studies, each 10 μg/m^3 increase was associated with a pooled hazard ratio of 1.18.[61] Another systematic review and meta-analysis on long-term exposures to ambient PM_{10} and forced expiratory volume in 1 second in healthy adults found each 10 μg/m^3 increase was associated with an 8.72 mL annual decrease in forced expiratory volume in 1 second.[62] A review and meta-analysis of eight studies on long-term exposure to $PM_{2.5}$ and respiratory mortality found a 10 μg/m^3 increase was associated with a pooled relative risk estimate of 1.05.[63]

Oxidative stress from the production of reactive oxygen species (ROS) has been identified as an important pathophysiological mechanism to explain associations between PM exposure and the occurrence of respiratory infections, and chronic cardiopulmonary diseases.[64] PM can contain many components capable of redox cycling such as transition metals, quinones, and secondary organic aerosols.[65–67] The inhalation and deposition of PM with these redox-cycling components can lead to chemical reactions that produce ROS (e.g., hydroxide ions (OH^-), superoxide ions (O_2^-), hydroperoxyl radicals (HO_2), hydrogen peroxide (H_2O_2), and O_3) in the epithelial lining fluid that covers the airways.[68] Excessive ROS production can overwhelm antioxidant defenses and trigger or enhance oxidative stress, cell death, biological aging, chronic inflammation, and allergies.[69]

Ambient Particulate Matter Pollution on Cardiovascular Health

Daily increases in PM increase the risk of cardiovascular morbidity and mortality.[70,71,80–88,72–79] In the US and Europe, acute PM exposures have been associated with increased hospital admissions for ischemic heart disease (IHD).[70,71] IHD is a term given to heart problems that result from the narrowing of the heart's arteries (coronary arteries) that supply blood to the heart muscle. The narrowing of coronary arteries can be caused by blood clots, constriction of the blood vessels (vasoconstriction), or the buildup of plaques on the inner walls of arteries (atherosclerosis).[89] Acute and chronic PM exposures have been found to increase the risk of thrombosis (the formation of blood clots),[72–75] vasoconstriction,[76–81] and atherosclerosis.[75,82–84] When blood flow to the heart is completely blocked, heart muscle cells (cardiac myocytes) die, which is known as a heart attack or a myocardial infarction (MI).[89] A systematic review and meta-analysis assessed and quantified the association between acute exposure to major air pollutants and MI risk. Researchers found acute $PM_{2.5}$ and PM_{10} were associated with a 2.5% and 0.6% increased risk (respectively) of MI,[85] per 10 μg/m^3 increase. Acute exposures have also been associated with increased risks of cardiac arrhythmias, a group of conditions that cause a heart to beat irregularly, too slowly, or too quickly.[86–88] PM exposure appears to affect cardiac arrhythmias by impacting the activity of the autonomic nervous system.

Chronic exposures to PM have also been associated with cardiovascular morbidity and mortality.[90–92] Amongst postmenopausal women in US metropolitan areas, chronic $PM_{2.5}$ levels were assessed of their relationship with risk of cardiovascular events (MI, coronary heart disease, stroke, and death from either IHD or cerebrovascular disease) and risk of death from cardiovascular disease (CVD). Chronic exposures to $PM_{2.5}$ was associated with 24% increased risk of a cardiovascular event and a 76% increased risk of death from CVD, per 10 μg/m^3 increase.[90] In a meta-analysis, the effect of chronic exposure to PM on incidence of acute coronary events was studied amongst 11 cohorts across Finland, Sweden, Denmark, Germany, and Italy. A 5 μg/m^3 increase in the annual mean $PM_{2.5}$ was associated with a 13% increased risk of coronary events, while and a 10 μg/m^3 increase in annual mean PM_{10} was associated with a 12% increased risk of coronary events.[91] In a systematic review of the relation between chronic exposures to ambient air pollution and chronic diseases, chronic exposures to $PM_{2.5}$ was associated with a 12 to 14% increased risk of total cardiovascular mortality, per 10 μg/m^3 increase.[92]

As mentioned in the *Impact of Particulate Matter on Respiratory Health* subsection, the generated ROS from PM exposure causes many harmful oxidation reactions throughout the body, resulting in oxidative stress and systemic inflammation.[93]

Systemic inflammation leads to increases in common carotid artery intima-media thickness, coronary calcification,[94,95] atheromatous plaque destabilization and rupture,[96] progression of atherosclerosis,[97] and thrombus formation.[96] In particular, increases in inflammatory cytokines IL-6 (also associated with exposure to $PM_{2.5\text{-}10}$)[98] and C-reactive protein (also associated with exposure to $PM_{2.5}$)[99] have been associated with the development of acute MI.[100,101]

Another physiological pathway whereby PM exposure causes indirect toxic effects to cardiovascular health involves the autonomic nervous system. The autonomic nervous system plays a key role in the control of heart rate and heart rate variability, both of which happen to be predictors of cardiac death in heart failure (HF).[102] Recent studies have shown increased PM exposure (particularly $PM_{2.5}$) to be associated with decreased heart rate variability.[103–108] A proposed mechanism suggests that several lung receptors and nerve endings in the lungs are able to "sense" PM or its redox-cycling components upon exposure.[109,110] The subsequent alterations in heart rate, heart rate variability, and blood pressure after PM exposure appear to reflect an acute autonomic nervous system imbalance favouring the sympathetic (responsible for stimulating the body's "fight or flight" response) over the parasympathetic (responsible for stimulating "rest and digest" activities) limb.[109–112] This autonomic nervous system imbalance can trigger acute cardiovascular events in the short-term (e.g., arrhythmias) and can contribute to chronic disease states (hypertension and vascular hypertrophy) in the long-term.[109]

Particulate Matter and Associations with Cancer

The International Agency for Research on Cancer (IARC) has classified ambient PM air pollution as a human carcinogen.[4] PM may contain many mutagenic chemical substances that can induce DNA damage, promote malignant neoplasms, and ultimately result in carcinogenesis.[64] Two mechanisms by which PM pollution leads to mutagenesis, and ultimately cancer, involve oxidative damage to DNA and the formation of bulky DNA adducts.[113,114] As has been mentioned in previous sections, the carrying of redox-cycling components within PM pollution is largely responsible for the generation of hydroxyl radicals[115,116] and ROS[117–119] in the body and subsequent oxidative damage to DNA. Alternatively, DNA adducts are segments of DNA bound to a cancer-causing chemical such as PAH (a potential component of PM) or ROS. Upon exposure, PAHs are metabolized via oxidative pathways producing electrophilic reactive products that make covalent bonds with the nucleophilic centers in DNA (as well as with other nucleophiles in the cell like proteins). These covalent bonds result in DNA binding and mutations that if not effectively repaired, can lead to carcinogenesis.[120]

The designation of PM from outdoor air pollution to be a Group 1 carcinogen by the IARC was based on sufficient evidence of carcinogenicity in humans and experimental animals as well as strong mechanistic evidence.[121] A systematic review and meta-analysis of 18 studies examining exposures to $PM_{2.5}$ and PM_{10} with lung cancer incidence and mortality provided the quantitative summary of evidence for this decision by the IARC.[122] The meta-relative risk for lung cancer associated with long-term exposures to $PM_{2.5}$ was 1.09 (95% CI: 1.04, 1.14) and with PM_{10} was 1.08 (95% CI: 1.00, 1.17).[122] While the IARC's decision was based on evidence of increased lung cancer risk with PM, there appears to be evidence that PM may be associated with increased risk of other cancers as well.[36] In addition to lung cancer, chronic exposures to $PM_{2.5}$ have been associated with an increased risk of mortality from liver cancer, colorectal cancer, bladder cancer, and kidney cancer.[36] Chronic exposures to PM_{10} have been associated with an increased risk of mortality from pancreas cancer and larynx cancer.[36]

2.1.4. Air Quality Guidelines for Particulate Matter Pollution

Ambient air quality guidelines are health and environmental-based air quality objectives for outdoor air pollution concentrations. These guidelines act as drivers to improve air quality for its specific location, whether province or state specific, country specific, or globally. In Canada, the 24-hour and annual standard concentrations for ambient $PM_{2.5}$ (as of 2020) are 27 μg/m^3 and 8.8 μg/m^3, respectively.[123] As for the World Health Organization (WHO), the 24-hour and annual standard concentration values for ambient $PM_{2.5}$ (as of 2018) are 25 μg/m^3 and 10 μg/m^3, respectively.[124]

2.1.5. Methods for Characterizing Ambient Air Pollution

There are several different approaches to characterizing exposure to ambient PM. At the local scale, fixed-site stationary monitoring allows for pollution concentrations to be measured continuously, and therefore, can describe short-term (i.e., daily, hourly) fluctuations.[125] This approach to measuring pollution has been used to assess health impacts of daily changes in pollution. Data from these monitors can also be used to identify air pollution concentrations that exceed regulatory thresholds. A monitoring 'network' of sorts usually needs to be implemented to be able to describe spatiotemporal variations in air pollution levels. While networks of stationary monitors may work for neighborhood scale monitoring, it can rapidly become expensive if city-wide monitoring is the objective. Capturing within-city variation in pollution levels is important, as anthropogenic and environmental conditions are known to change rapidly on small spatial scales.[126] Fortunately, other methods such as mobile monitoring or predictive modeling can be used to characterize within-city variation in air pollution levels.

Mobile monitoring, whether done while driving, riding a bicycle, or walking may allow for improved spatial coverage of air pollution measurements. Predictive modeling spans an array of methods (e.g., land use regression (LUR), atmospheric dispersion modeling)[127–129] to estimate air pollution levels across an area based off of existing data. LUR modeling can be an alternative to capture within-city variation as it only requires a) monitoring at a small number of locations and b) the development of stochastic models using predictor variables (land use, distance to roads, road length, etc.) that can usually be obtained from geographic information systems.[127] Atmospheric dispersion models involve the mathematical simulation of how air parcels disperse in the atmosphere, downwind from their source locations. Dispersion modeling requires inputs from emissions and meteorological data to estimate pollutant concentrations. Generally, dispersion models are used to estimate pollutant concentrations under different scenarios in the future.[128,129]

Satellite sensors are capable of monitoring air pollution over large geographical areas. Satellite instruments such as Moderate Resolution Imaging Spectrometer and Multiangle Imaging Spectro-Radiometer are able to collect Aerosol Optical Depth (AOD) data that, when combined with the use of global chemical transport models, can estimate ground-level $PM_{2.5}$ concentrations.[130] While the relationship of satellite-derived AOD and ground-surface $PM_{2.5}$ is spatially and temporally heterogenous (due to aerosol vertical distribution, humidity, and aerosol composition),[131] they do appear to relate well.[132] The spatial resolution for satellite-derived AOD appears to range from 0.250 by 0.250 km to 10 by 10 km per pixel,[133–135] and has been improving over time. The main advantage of satellite remote sensing lies in its ability to capture large-scale, regional and global distributions of PM that fixed-site ground-level monitors are not capable of.[136]

2.2. Ambient Air Pollution in Grenada

Grenada is situated in the West Indies in the Caribbean and its neighboring island of Carriacou is only 50 km to the north. Land use on the island is subdivided into the following: forest (50%), agricultural land (32.3%), and other (17.7%). Grenada's economy relies heavily on tourism as well as revenue generated by St. George's University. Contributing to Grenada's GDP are its services (77.7%), industrial (15.5%), and agricultural sectors (6.8%).[6] The main industries of the island involve food and beverages, textiles, light assembly operations, tourism, construction, education, and call-center operation.[6] The main agricultural products of Grenada are bananas, cocoa, nutmeg, mace, soursop, citrus, avocados, root crops, corn, vegetables, and fish.[6]

Grenada is one of many islands in the Caribbean that has lacked any continuous ground-based systematic monitoring of ambient air pollution. Grenada has several distinct sources of air pollution that include local and regional sources. These sources of air pollution are described in greater detail below.

2.2.1. Electricity

As of 2014, approximately 40% of Grenada's energy consumption stemmed from its electricity generation.[137] As of 2017, commercial activity, domestic (home usage) activity, and industrial activity accounted for an estimated 55.4%, 39.7%, and 2.7% of Grenada's electricity sales, respectively.[138] Of Grenada's total electricity generation, 96% is generated from the burning of fossil fuels and 4% is generated from renewable sources of energy.[6]

2.2.2. Motor Vehicles

As of 2014, slightly less than 40% of Grenada's energy consumption is due to the transportation sector.[137] Grenada's automotive fleet consists of approximately 27,000 vehicles with an annual average increase of 1,200 vehicles. While there is a significant market for imported used vehicles, the import of new vehicles relative to total vehicle imports has been on the rise as it went from 61% in 2006 to 77% in 2008. As of 2014, low sulphur diesel fuel was introduced to Grenada to reduce the country's overall energy consumption and carbon footprint.[137] Though, while low sulphur fuels are present in Grenada, regulations still allow the use of high sulphur fuels.[139] In addition, Grenada has not adopted European vehicle emission standards.[139] This is relevant as these standards take into account pollutant emissions from vehicles such as NO_X, CO, and PM. Another key aspect of Grenada's transport sector is public transport, as minibuses and taxis are commonly used by island residents.[139]

2.2.3. *Open Waste Burning*

Open waste burning is an important source of local anthropogenic pollution in Grenada. It is used to manage crop fields and solid municipal waste. In the agricultural context, open waste burning clears land for cultivation purposes and removes much of the built-up dry vegetation matter, thus creating space for new crops to flourish.[140] In residential areas, the burning of plant materials and organic waste from areas around residents' homes is common and referred to as "household bush burning". For solid municipal waste, open waste burning is more a waste-reduction method as it results in disposable ash materials that is of reduced volume than the initial waste.[141] These burning practices emit particulate matter, including $PM_{2.5}$ and black carbon (a significant component of PM) in surrounding air. Open waste burning produces 2.5 times more black carbon than other confined combustion practices.[142] While all Caribbean countries practice open waste burning for at least one form of waste (agricultural or municipal), as of 2017, only two Caribbean countries (Jamaica and Barbuda) had legal frameworks prohibiting this practice without permission.[139]

2.2.4. *Ocean-Going Vessels*

As Grenada is an island, much of its supplies and products are imported or exported via sea shipment. The presence of nearby ocean-going vessels, regardless if they are carrying freight or tourists, impacts coastal air quality.[143–145] Ocean-going vessels are typically powered by diesel engines which emit a wide range of pollutants including hydrocarbons, SO_X, NO_X , and PM.[146] As the emission of these pollutants at marine ports result in diminished air quality and human health in surrounding areas, they are also of interest.[147] A review on the impact of harbour activities on local air quality reports based off 23 case studies (North America – 3, Asia – 6, Europe – 14) found that ship emission contributions to local ambient $PM_{2.5}$ concentrations in harbour cities differed both between and within regions: Europe (2-14%), Asia (1-25%), and North America (3-29%).[148] This demonstrates the effect ship traffic alone can have on air quality of nearby ports/port-cities and is especially relevant to Grenada.

2.2.5. Local Industry

Grenadian rum distilleries also contribute to ambient air pollution. Boilers are commonly used in rum distilleries to generate heat for the distillation process. A new rum distillery in Grenada, Renegade Rum, uses bagasse (organic, shredded sugar cane debris left over from milled sugar cane) to fuel their boilers instead of fossil fuels such as oil or coal.[149] Though, using a complex three-part system, the bagasse is burned at very high temperatures, filtered of the coarse ash and cinders, leftover sooty combustion gases, and fine ash particles before exhaust air exits the facility chimney.[149] This system has allowed Renegade Rum distilleries to have a particulate emission standard for its bagasse boilers to be 50 mg/Nm^3 (milligrams/cubic metre of air at 25 Celsius and 1 atm pressure).[149] Another rum distillery in Grenada, River Antoine Rum Distillery, uses wood fire to distill their rum[150] which may be a source of PM pollution to surrounding areas and can result in health effects.[151] Other local businesses in Grenada such as chocolate production facilities and beer breweries likely use grid power as their predominant sources of electricity.

2.2.6. Sea-Salt Aerosols

Sea-salt spray represents another source of PM, but strictly speaking are not referred to as air pollution. Sea-salt aerosols are defined as the aerosol component consisting of seawater drops and sea-salt particles. The radii of these aerosol particles range from 0.1 to 1000 μm and are a major contributor to the mass of PM injected into the atmosphere globally.[152] The breaking of waves in the surf zone can produce sea-salt aerosols and affect coastal areas up to 25 km inland from the coastline.[153,154] Sea-salt aerosols interact with urban atmospheric pollutants (sulphuric and nitric acid) from coastal cities to produce sodium sulphates and nitrates together with hydrochloric acid gas.[155] In a simulation of atmospheric chemical dynamics over Greece, sea-salt aerosols comprised up to 60% of PM_{10} and only 10% of the $PM_{2.5}$ near the coast, though sea-salt aerosol's contribution decreased rapidly further inland.[155]

2.2.7. North African Desert Dust

Each year in the Caribbean, residents are exposed to episodic plumes of desert dust that are transported across the Atlantic Ocean from North Africa. A prime example of this is the dust episode of June 2020 that was the most significant Caribbean NADD episode in the past 50 years.[156] A visualization of the impacts of this storm in Grenada is provided below.[157]

Figure 2*: Photographs of Grenada on a clear day and a day with North African desert dust.*[1]

The Sahara and Sahel regions of North Africa represent the largest source of dust (a major component of PM) in the atmosphere. Estimates from Tanaka and Chiba (2006) indicate North Africa may account for approximately 58% of the global dusts.[158] Recent estimates of annual dust emissions sourced from North Africa have ranged from 400 to 2200 Tg/yr.[159]

Formation and Transport of North African Desert Dust

NADD particles primarily result from the progressive abrasion of rocks at source locations. They mostly comprise of mineral matter such as clays, quartz, calcium carbonates and sulphates, as well as feldspars, iron, and other metal oxides in minor quantities. Though, long-range transport preferentially selects for smaller, more aerodynamic particles such as clays due to their fine-layered platelet structures.[9] Particles also tend to include biological and chemical components. NADD particles are covered with organic matter such as plant detritus, pollen, bacteria, viruses, and fungal spores. In

[1] On the left, a picture of Grenada's coast on a day with no North African desert dust. On the right, a picture of Grenada's coast during the June 2020 North African desert dust episode. Photos taken by Dr. Kerry Micthell (St. George's University) and published with permission.

addition, anthropogenic toxins such as pesticides, herbicides, and industrial emissions are known to adsorb onto NADD particles from aerosolization during dust plume formation or by being collected during transport.[10]

Despite the continuous transatlantic transport of NADD to the Caribbean, it is also widely distributed to other areas of the world. NADD has four main transport trajectories: 1) ~60% southward transport to the Sahel and the Gulf of Guinea, ~25% westward transport to the Atlantic Ocean, ~10% northward transport to Europe, and ~5% eastward transport to the Middle East.[160] Westward transport of NADD across the Atlantic arises primarily from the regions of central and southwestern Algeria, Mali, and Mauritania.[161]

Westward transport of NADD across the Atlantic varies seasonally. During Northern Hemispheric summer (June-November), the northern latitudinal shift of the Intertropical Convergence Zone causes a deepening of the boundary layer over northern Africa. This results in increased surface heating of northern Africa which causes an increase in dry convection and convergence. Therefore, in areas where dust emissions are possible, this increased surface heating produces dusty convective plumes and dust devils that result in more dust transport to higher altitudes. The uplifted dust plumes are then transported westward within a stable air layer known as the Saharan Air Layer that resides at altitudes up to 6 km high, above the moist trade winds.[161] The Saharan Air Layer is what is most responsible for the transatlantic transport of NADD to the Caribbean during summer months.[161–164]

In the Northern Hemispheric winter (December-May), conditions allow for the transatlantic transport of NADD to South America. During this season, dust emissions sourced from the Bodélé Depression (the largest dust source in the Sahara and Sahel) are at their maximum. Transported in a southwestern direction within the trade wind layer, via the Harmattan winds, these dusty air parcels can reach altitudes of up to 1.5 km. This is integral as long-distance dust transport across the Atlantic is only possible if it occurs at high altitudes. In addition, the southern latitudinal shift of the Intertropical Convergence Zone allows for such dusty air parcels to reach latitudes as low as the Amazon Basin in South America.[161,163,164]

North African Desert Dust Components and Human Health

When examining the impact of desert dust particles on human health, certain components may be particularly responsible for health effects. Of the bacteria isolated from NADD particles, approximately half were gram-negative.[10] Gram-negative bacteria have a thin layer of peptidoglycan and an outer lipid membrane (containing lipopolysaccharide, also known as bacterial endotoxin),[10] whereas gram-positive bacteria have a thick peptidoglycan layer and no outer lipid membrane.[165] Endotoxin has been shown to be a potent inflammatory agent that may result in chronic airway disease.[166] Collected across the Atlantic Ocean, the amount of endotoxin measured at the edge of a NADD storm was found to be 12 times higher than that found at background levels.[167] Thus, given the high frequency and volume of annual NADD exposure in the Caribbean, bacterial endotoxin may contribute to an increased incidence of asthma in the region.[168]

Many bacterial species that are known to be human pathogens, and impact human health, have been isolated from NADD samples, including: *Kocuria rosea* (bacteremia), *Gordonia terrae* (nervous system, skin),[169] *Brevibacterium casei* (sepsis),[170] *Staphylococcus epidermis* (endocarditis, urinary tract infections),[171] and *Pseudomonas aeruginosa* (fatal infections in burn patients).[172] Fungi species are allergens, and can cause asthma attacks, hay fever, and even pneumonitis.[173] While some NADD events have yielded relatively low viable fungi concentrations, dead fungal materials within the dust may trigger allergic reactions.[173]

Due to the clays that make up most of the mineral matter in NADD, there is abundant quantities of silicates within these dust particles. In a given NADD episode, silicates can make up 60-70% of the particle volume at a 4-10 μm size range, and 70-85% of the particle volume at the 2.4-4 μm size range.[9] This is relevant because it has been suggested that allergic inflammation from mineral dust exposure may be due to the presence of mineral components such as silica and quartz.[174]

Desert Dust and Human Health

Epidemiological studies have evaluated the impacts of desert dust exposures (mostly acute exposures) on human health. This section summarizes findings from these studies that have examined cardiorespiratory morbidity and mortality. In total, 27 such studies were identified (see Table A7 in Appendix A). Study locations include Europe (thirteen), Asia (six), the Caribbean (five), the Middle East (two), and North America (one). Most of these studies have used some variation of an ecological, time-series, or case-crossover study design. The studies varied in terms of the age distribution of the participants.

Of the 17 studies that examined desert dust exposures and respiratory and cardiovascular morbidity, 13 were focused on respiratory morbidities and five were focused on cardiovascular morbidities. In general, the occurrence of desert dust days was associated with modestly increased risks for cardiovascular and respiratory hospital admissions relative to non-desert dust days. Of the 10 studies that examined desert dust exposure and respiratory, cardiovascular, and all-cause mortality, five involved respiratory mortality, seven involved cardiovascular mortality, and four involved all-cause mortality. The relationship between desert dust exposure and respiratory mortality across these studies was inconsistent. There appears to be a positive association between desert dust exposure and cardiovascular mortality as five of the seven studies demonstrated such an association as statistically significant. The relationship between desert dust exposure and all-cause mortality also appears to be inconsistent.

Desert Dust and Human Health in the Caribbean

There are eight previously published studies that examined associations between NADD and human health in Caribbean nations. Seven of these studies are summarized below, while the remaining study is described in greater detail in section entitled *Previous Epidemiological Studies of Air Pollution in Grenada*.

In Trinidad, Gyan et al. (2005) used a time-series study to investigate the association between pediatric asthma hospital admissions and NADD cloud cover based measures of NADD.[175] Researchers identified NADD days using visibility measures provided by the local meteorological office. Specifically, days with a visibility of less than 15 km were classified as NADD days. Pediatric asthma hospital admissions included those presenting with an asthmatic attack or those who received bronchodilator nebulization. Using a Poisson regression model, a decrease in visibility from 16 km (indicating no dust) to 7 km (indicating very dusty conditions) was associated with an increased daily pediatric asthma admission rate from 7.8 to 9.25 admissions per day. This result was produced while adjusting for barometric pressure, humidity, and temperature.

Prospero et al. (2008) published findings from a time-series analysis of daily concentrations of dust and pediatric asthma hospital admissions in Barbados.[176] Daily measures of aerosol were derived using samplers that were approximately 47 m above the ground (to minimize local aerosol source contribution) on the easternmost coast of Barbados. Subsequent sampling was done to assess mineral dust content. Pediatric asthma hospital admissions were tabulated based on those who presented with "wheezing", "tightness in the chest", or "shortness of breath". The study reported no association between daily dust concentrations and pediatric asthma admissions.

Elsewhere, Cadelis et al. (2014) used a time-stratified case-crossover study to investigate the impacts of PM_{10} and $PM_{2.5-10}$ contained in NADD on pediatric asthma emergency department admissions in Guadeloupe in 2014.[177] NADD days were identified using the Naval Research Laboratory's Navy Aerosol Analysis and Prediction System (NAAPS) that produces forecast maps/animations of surface PM concentrations for sulphate, dust, smoke, and total optical depth.[178] PM_{10} and $PM_{2.5-10}$ data were obtained from four fixed-site monitoring stations across Guadeloupe. The study reported an increased risk of emergency visits on dust days compared to non-dust days. Per 10 $\mu g/m^3$ increase in PM_{10} and $PM_{2.5-10}$ on NADD days and non-NADD days, the excess risk percentages for emergency asthma visits for children aged 5 to 15 were found to be higher on NADD days (PM_{10}: 9.1%; $PM_{2.5-10}$: 4.5%) than non-NADD days (PM_{10}: 1.1%;

$PM_{2.5-10}$: 1.6%). No significant effect was found for a 10 μg/m^3 increase in $PM_{2.5}$ when comparing NADD days and non-NADD days.

In Puerto Rico, Ortiz-Martinez et al. (2015) used a retrospective correlational study to examine if pediatric asthma hospital admissions were correlated with PM_{10} during NADD days and non-NADD days in 2004 and 2005.[179] NADD days were defined as days in which PM_{10} concentrations were above the background level of 18.3 μg/m^3 on days with aerosol clouds over Puerto Rico, using satellite images from Total Ozone Mapping Spectrometer. Pediatric asthma hospital admissions were measured by total services offered to asthma cases. Pediatric asthma hospital admissions during NADD days were associated with rural site (Pearson Correlation Coefficient = 0.548) and urban site PM_{10} (R = 0.470).

In Guadeloupe, Viel et al. (2019) used a retrospective longitudinal study to investigate the impact of NADD episodes on preterm births amongst a cohort of 909 pregnant women, from 2004 to 2007.[180] NADD episodes were determined using mean daily PM_{10} concentrations measured from a background air quality monitoring station in Guadeloupe, where ≥ 55 μg/m^3 indicated intense dust. Daily PM_{10} concentrations and proportion of NADD episodes were recorded for each woman's pregnancy. Preterm births were defined as a birth before 37 completed weeks of gestational age. The authors did not provide any measure of association to describe how exposure to intense NADD episodes increased the risk of preterm births. However, when considering preterm births, an adjusted odds ratio (OR) of 1.54 (95% CI: 1.21-1.98) was found per 4.06% increase in proportion of days during pregnancy with intense NADD episodes.

Also in Guadeloupe, Viel et al. (2020) used a retrospective longitudinal study to investigate the impact of NADD episodes on small for gestational-age births amongst a cohort of 919 pregnant women, from 2004-2007.[181] NADD exposure was assessed by mean daily PM_{10} concentrations, measured from a background air quality station, averaged across each woman's pregnancy. Severe small for gestational age was determined based off French fifth percentiles for gestational age at delivery and infant gender using weight, length, and head circumference measures. The authors did not provide any measure of association to describe how exposure to NADD episodes increased the risk of symmetrically growth-retarded births (weight, length, and head circumference of the baby were all below the fifth percentile measures), though, they did find each 3.08 $\mu g/m^3$ increase in PM_{10} was associated with an adjusted OR of 3.28 (95% CI: 1.08-10.02).

In Guadeloupe, Tuffier et al. (2021) used a retrospective ecological study to compare the value of Aerosol Optical Thickness (AOT) retrievals to ground-level PM measurements, measured from a background station, in retrospectively assessing NADD exposure during pregnancies from 2005-2008.[182] In addition, AOT based NADD estimates were examined of their association with preterm births from 2005 to 2008. The local air quality agency in Guadeloupe justifies using PM_{10} concentrations to classify NADD episodes because anthropogenic particle pollution is generally low (approx. 20 $\mu g/m^3$) on the island due to the absence of heavy industry and year-round trade winds. Averaged AOT_{470} (AOT retrievals in the blue band, ranging from 0 (maximum visibility) to 4.0 (minimum visibility)) values and ground-level PM_{10} measurements during pregnancies were found to have a moderate correlation (R^2 = 0.29). Authors reported that a 0.04 increase in AOT_{470} based NADD exposure estimates was associated with a non-statistically significant adjusted OR of 1.18 (95% CI: 0.95-1.47) for the occurrence of preterm births.

2.2.8. Biomass Burning Smoke

Biomass burning is an important regional source of ambient air pollution in Grenada and other Caribbean nations. In the Sudano-Sahel region of Africa, savannah fires produce plumes of dust and smoke that get transported across the Atlantic to the Caribbean and South America.[183–185] In addition, forest fires and agricultural burning from northern South American countries produces smoke which also impacts southern Caribbean islands such as Trinidad, Tobago, and Grenada.[186,187]

2.2.9. Previous Epidemiological Studies of Air Pollution in Grenada

To date there have been only two published air pollution studies in Grenada. The first study, by Akpinar-Elci et al. (2015a), used a retrospective ecological study design to investigate the relationships between mean monthly NADD concentrations, measures of climate variables and asthma-related hospital visits to the emergency room in Grenada. Associations between these variables were examined using data collected from January 1, 2001 to December 31, 2005.[8] Asthma emergency room visit data were obtained from the main hospital on the island which is just outside St. George's. Hourly climate variable (visibility, rainfall, mean sea level pressure, relative humidity) data were collected from the meteorological office at the Maurice Bishop International Airport. Daily NADD concentration data were collected from the Environmental Protection Department in

Barbados. The authors reported variation in mean monthly asthma visits demonstrated a very weak association with mean monthly dust concentration ($R^2 = 0.04$), while a similar finding was observed between monthly average rainfall and dust concentration ($R^2 = 0.07$). The study reported that asthma visits were increased during the rainy season. An important limitation of this study was the reliance on estimates of dust concentration measurements from Barbados. The study also did not evaluate associations between day-to-day changes in air pollution with corresponding changes in daily hospitalization, nor did it control for other confounding variables including meteorology.

In a cross-sectional study, Akpinar-Elci et al. (2015b.) investigated associations between household bush burning and the prevalence of respiratory symptoms.[140] Information was collected from residents of Grenada using a standardized questionnaire that was given to households in a rural area (St. Andrew) and an urban area (St. George) of Grenada. The survey included questions on demographics, bush burning practice, airway symptoms, physician-diagnosed diseases, environmental health-related history, and smoking status. In total, 225 participants completed the questionnaire, with a participation rate of 80.1%. The practice of bush burning on a monthly basis was reported by 43% of households. Of those that regularly practiced bush burning, 71% did it once per month, while the remaining 29% reported doing it twice monthly. The prevalence of those who burned bush was higher in rural than urban areas. Compared to those who did not burn bush, those who reported bush burning had a higher prevalence of sinusitis symptoms (OR:2.1), and a higher prevalence of physician-diagnosed sinusitis (OR:1.4), physician-diagnosed asthma (OR:1.3), and cough (OR:1.5).[140]

Altogether, the study by Akpinar-Elci et al. is unique as there are few other studies on the work of small-scale household bush burning and respiratory symptoms in the economically developing world. A strength of this study is that it demonstrates those who practice bush burning in Grenada may be more likely to have adverse respiratory conditions compared to those who do not bush burn. As the practice of household bush burning is common across the island, the authors suggested that a limitation of the study was that residents who did not practice household bush burning may still get exposed to some of these air pollution emissions from neighbours. They posited that this potential limitation may contribute to misclassification bias in the computation of odds ratios and result in mischaracterizing the association between bush burning and prevalence of respiratory symptoms.[140]

2.3. Impact of COVID-19 on Concentrations of Ambient Air Pollution

In late December of 2019, a novel coronavirus that would later be named severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) was identified in Wuhan, China. SARS-CoV-2 is the cause of the coronavirus disease, COVID-19.[188] On January 30th, the WHO declared a worldwide public health emergency regarding the global outbreak and spread of COVID-19. On March 11th, the WHO declared coronavirus pandemic.[189] While there has been diversity in the strategies used to combat the spread of COVID-19, nearly all countries have implemented some form of restrictions to reduce person to person disease spread. Consistent among most lockdown measures are restrictions on transportation and industrial activities, two main sources of ambient air pollution. Thus, the pandemic provides the opportunity to examine how abrupt changes in human activity from these restrictions impacted air quality.

2.3.1. Exposure Studies of the Impact of COVID-19 on Air Pollution

A series of studies have reported on the changes in air pollution during COVID-19. These restrictions included stay at home orders, travel restrictions, and closures of non-essential businesses. In Table 1, 19 studies examining the impacts of COVID-19 on ambient PM pollution have been summarized. Research articles were included from Asia (eight), the Middle East (two), Europe (three), North America (three), and South America (three). Studies were examined up until September 2020. For selected articles, most locations of study had some form of mobility restrictions or "lockdown" implemented in February or March 2020.

For the most part, these studies reported concentrations of ambient PM pollution during these lockdown periods when compared to concentrations measured during the same time period in previous years. Decreases in concentrations of PM_{10} and $PM_{2.5}$ appear to mostly be due to restricted movements of traffic and temporary closures of factories and industries.[190–192] However, decreases in PM have not been as great as the decreases in NO_X.[12] This is likely due to the fact that NO_X concentrations are due primarily to traffic related pollution, whereas PM is influenced by regional as well as local sources.[190]

While decreased $PM_{2.5}$ concentrations during the lockdown were reported in most studies, some analyses found pollution levels increased.[193–195] Le et al. (2020) posit that their observations of increased concentrations in Beijing, China are a result of higher than normal relative humidity, reduced precipitation and wind speeds, and a lower planetary boundary layer height.[193] In Tehran, Iran, Broomandi et al. (2020) suggested that a combination of dust storm occurrence, reduced precipitation, relative humidity, and planetary boundary layer height, and increased temperature may explain increased lockdown $PM_{2.5}$.[194] According to Bekbulat et al. (2020), substantial random and systematic variability as well as changes in other air pollutant concentrations that may influence the formation of secondary PM are thought to explain the slight increase in $PM_{2.5}$ across the US throughout the period where initial "stay-at-home" orders were issued.[195]

***Table 1**: Summary of studies examining the impact of COVID-19 on ambient PM pollution, up until September 2020.*

Author	Location	Lockdown/State of Emergency Commencement Date	Comparison Time Period vs. Referent Time Period	Pollutant	% Change in Concentrations
Asia					
Le T, et al. (2020)[193]	Wuhan, China	January 23, 2020	January 23 to February 13, 2020 vs. January 23 to February 13, including Lunar New Year from 2015-2019	$PM_{2.5}$	-32.4%
	Beijing, China	February 10, 2020			+23.4%
Nichol JE, et al. (2020)[196]	Beijing, China	February 10, 2020	January to March 2020 vs. January to March 2019	$PM_{2.5}$	+1.8%
	Tianjin, China	February 6, 2020			-5.1%
	Nanning, China	February 5, 2020			-6.8%
	Urumqi, China	No apparent lockdown from January to March			-20.3%
He G, et al. (2020)[197]	China	Cities in China that locked down from January 1 to March 1, 2020 commenced lockdown between January 23 to February 13, 2020	January 1 to March 1, 2020 vs. January 1 to March 1, 2019	$PM_{2.5}$	-24% *In locked-down cities* -7% *In non-locked down cities*
Ma CJ and Kang GU (2020)[198]	Wuhan, China	January 23, 2020	Month after lockdown in each city vs. Month before lockdown in each city	$PM_{2.5}$	-29.9%
	Daegu, South Korea	February 23, 2020			-20.9%
	Tokyo, Japan	March 25, 2020			-3.6%
Wang L, et al. (2020)[199]	Hangzou, China	February 4, 2020	January 24 to February 15, 2020 vs. January 24 to February 15, 2019	$PM_{2.5}$	-42.7% (city) -18.5% (rural)
				PM_{10}	-47.9% (city) -39.6% (rural)
Sharma S, et al. (2020)[200]	22 cities across India	March 24, 2020	March 16 to April 14, 2020 (lockdown period) vs. March 16 to April 14, 2017-2019	$PM_{2.5}$	-43%
				PM_{10}	-31%
Singh RP and Chauhan A (2020)[201]	New Delhi, India	March 22, 2020	March 22 to 31, 2020 (lockdown period) vs. March 2020	$PM_{2.5}$	-27.57%
	Mumbai, India				-19.25%
	Hyderabad, India				-3.99%
	Kolkata, India				-34.52%
	Chennai, India				-5.40%
Zhu Y, et al. (2020)[202]	Singapore	April 7, 2020	February 15 to June 1, 2020 (Circuit breaker policy (restrictions on business, social, and other activities) from April 7 to June 1, 2020)	$PM_{2.5}$	-1-2% **per 10 percentage point decrease in mobility*
Middle East					
Kerimray A, et al. (2020)[203]	Almaty, Kazakhstan	March 19, 2020	March 19 to April 14, 2020 (lockdown period)	$PM_{2.5}$	-21%

			vs. March 19 to April 14, 2018-2019		
Broomandi P, et al. (2020)[194]	Tehran, Iran	March 21, 2020	March 21 to April 21, 2020 (lockdown period) vs. March 21 to April 21, 2019	$PM_{2.5}$	+10.50%
				PM_{10}	-11.33%
			Europe		
Tobías A, et al. (2020)[190]	Spain	March 14, 2020	March 14 to March 30, 2020 (lockdown period) vs. February 16 to March 13, 2020 (pre-lockdown period)	PM_{10}	-28% (traffic monitoring station) -31% (urban background station)
Dobson R and Semple S (2020)[204]	Scotland	March 23, 2020	March 24 to April 23, 2020 (lockdown period) vs. March 24 to April 23, 2017-2019	$PM_{2.5}$	-12.4%
Higham JE, et al. (2020)[205]	United Kingdom	March 23, 2020	March 23 to June 30, 2020 (lockdown period) vs. March 23 to June 30, 2013-2019	$PM_{2.5}$	-18.2%
			North America		
Bekbulat B, et al. (2020)[195]	United States	Most states implemented "stay-at-home" order from March 19 to April 6, 2020. Most states re-opened from April 24 to June 15, 2020.	March 19 to June 9, 2020 (post-COVID period, period in which activities in the US were noticeably affected by COVID) vs. March 5 to June 23, 2010-2019	$PM_{2.5}$	+3% **Relative to expected concentrations (temporally corrected historical medians) from same time period during 2010-2019*
Berman JD and Ebisu K (2020)[206]	United States		January 9 to March 12, 2020 Pre-COVID-19 Period (January 9 to March 12, 2017-2019)	$PM_{2.5}$	-3.75%
			March 13 to April 8, 2020 COVID-19 Period (March 13 to April 8, 2017-2019)		-4.45%
Adams MD (2020)[207]	Ontario, Canada	March 17, 2020 (Ontario State of Emergency)	(Week defined as epidemiological week) Week 8 to 12, 2020 [5 weeks prior to State of Emergency] (Week 8 to 12, 2015-2019)	$PM_{2.5}$	1 ug/m^3 lower
			Week 13 to 17, 2020 [During State of Emergency] (Week 13 to 17, 2015-2019)		No reduction
			South America		
Siciliano B, et al. (2020)[208]	São Paolo, Brazil	March 16, 2020 (Schools, universities closed, and gatherings prohibited, work from home advisory) March 23, 2020 (Partial lockdown - Non-essential businesses closed, industrial and	A) March 16 to March 22, 2020 (some restrictions) B) March 23 to April 3, 2020 (partial lockdown) C) April 4 to April 16, 2020 (partial lockdown relaxed)	PM_{10}	A) -8.1% B) -3.9% C) -2.5%
	Rio de Janeiro, Brazil				A) +20.1% B) -18.6 C) +9.4%

		construction activities suspended)	vs. February 16 to March 15, 2020 (before restrictions)		
Dantas G, et al. (2020)[209]	Rio de Janeiro, Brazil		March 23 to April 16, 2020 (partial lockdown) vs. March 23 to April 2019	PM_{10}	*-3.1% Percentage change of median values*
Zambrano-Monserrate MA and Ruano MA (2020)[210]	Ecuador	March 17, 2020 (Ecuador State of Emergency)	March 2020 (COVID restrictions) vs. March 2018-2019	$PM_{2.5}$	-35.1%

2.3.2. COVID-19 Public Health Interventions in Grenada

Grenada implemented a number of public health measures to reduce the spread of COVID-19. On March 16, 2020, the government of Grenada issued a cruise ship advisory that prohibited passengers from disembarking.[211] On March 20, all crew and passengers aboard pleasure craft (vessel used for recreation, pleasure, or daily living) and live-aboard (a vessel designed for people to live aboard it) were similarly prohibited from disembarking on the shores of Grenada, Carriacou, and Petite Martinique from sea, without the consent of an immigration officer.[212] On March 23, the government of Grenada closed off its airports to all commercial passenger traffic.[213] On March 25, a limited state of emergency in Grenada, Carriacou, and Petite Martinique was declared. From March 25 to April 1, the cabinet of Grenada implemented “Emergency Powers (COVID-19) Regulations, 2020”.[214] This entailed a curfew for citizens, only being allowed to leave their homes to conduct certain designated activities (being an essential worker, traveling to the doctor, pharmacy, grocery store, bank, credit union, money services, to refuel, or for daily exercise) between 5 AM and 7 PM. If a business was not capable of continuing business operations with its employees working remotely from home, the business was required to cease its operations. All religious and educational institutions were to remain closed, except for individual attendance at a place of worship.

Restrictions were also placed on the hosting or attending of social activities, all non-essential use of vehicles (i.e., road traffic), and public transportation.

In an update to the "Emergency Powers (COVID-19) Regulations", the government of Grenada enacted a mandatory 24-hour curfew from March 30 to April 6 in which all restaurants and gas stations were closed, and citizens were only able to leave their households for food or medical emergencies.[215] This curfew was then further extended from April 6 to April 20 with intermittent updates from the government.[216] These updates would advise citizens on which days they could go grocery shopping (termed a shopping day), do banking (termed a bank day), or go get gas for their motor vehicles (termed a gas station day). On such days, only one person per household was allowed to leave their residence.[217] During this extended mandatory curfew, Grenada had six shopping days (April 6, 11, 12, 16, 17, and 18),[217,218] one gas station day (April 9, 15, 17),[219] and two bank days (April 16 and 17).[218] From April 20 to April 27, the government of Grenada relaxed their State of Emergency protocol. While the 24-hour curfew was still in effect, the Monday, Wednesday, and Friday of that week were designated business days for shopping and businesses being open.[220] For this relaxed State of Emergency protocol, citizens were not allowed to drive a motor vehicle on any public or private road unless they were a public servant or essential worker, traveling to an establishment or business on a designated business day or in case of medical emergency.[221] From April 27 to May 5, the 24-hour curfew was maintained and Monday, Wednesday, Saturday, and Sunday were designated business days of the curfew period.[222] This curfew was then further extended from May 5 to May 12 with the Monday, Wednesday, and Friday being designated business days.[223] On May 11, it was made effective by the Grenada government that every day of the week will be a designated business day. Further, this meant that businesses granted permission to operate, could do so on every day of the week as long as hours of operation were within the 8 AM to 5 PM window.[224]

From June to August 2020, the resumption of education for all students of compulsory school age was implemented in 5 phases.[225] On June 29, the government of Grenada updated the citizen freedom of movement time period from 5 AM to 11 PM daily. Also, businesses already permitted to operate were able to do so until 10 PM daily.[226] The commercial reopening of Grenada's borders took into consideration the health risks posed by passengers coming from different regions of the world. From July 15 onwards, Grenada's international airport began accepting commercial flights from countries across the Caribbean region, viewed as low risk. From August 1 onwards, the international airport began accepting international flights from countries viewed as medium risk at the time. Only chartered flights from countries considered high risk were accommodated.[227] On August 10, Air Canada resumed service to the tri-island state of Grenada, Carriacou, and Petite Martinique[228] and on October 1, 3 international airlines resumed weekly flights to the tri-island state as well.[229–231]

Physical distancing practices from June 29, 2020 (Emergency Powers (COVID-19) Regulations) were renewed by the government of Grenada until September 16, 2020.[232] In this iteration of the Emergency Powers regulations, it was re-stated that "All seaports shall be closed to regional and international seafaring and private boating; and no person shall be permitted to enter and disembark for any reason…except with the permission of the Airports Authority and the Ministry of Health.".[232] On September 17, the Grenada government implemented the Public Health Act which replaced the Emergency Powers Regulations that had to be renewed on a fortnightly basis. The Public Health Act has many of the same regulations as the Emergency Powers Regulations (changed regulations are not relevant to this thesis project) but differs in that it will continue the State of Emergency indefinitely and become the 'new normal' for Grenada which has continued past the end of October, 2020.[233] The table below documents monthly counts of new COVID-19 cases in Grenada from March to October 2020. During this time period, there were no observed deaths at any point from COVID-19.[234]

Table 2*: Monthly numbers of newly diagnosed COVID-19 cases in Grenada from March to October 2020.*

Month	COVID-19 Cases
March	9
April	11
May	3
June	0
July	1
August	0
September	0
October	4
Total	28

2.4. Overall Summary and Study Rationale

Air pollution is an environmental exposure that has substantial human health impacts. To date, the island of Grenada (like most other Caribbean islands) has lacked any continuous systematic monitoring of ambient air pollution. Monitoring ambient air pollution is an integral part in maintaining public health, and measurement allows for the health impacts of pollution to be estimated. The sources of pollution in Grenada differ from other countries, including North African desert dust events.

In addition, the unprecedented COVID-19 pandemic changed the manner in which people work, travel, and interact with others. As a result, ambient air pollution concentrations have likely been impacted. These impacts have been assessed in several countries, however, to date, no such evaluation has been done in a Caribbean nation. This thesis directly addresses this gap.

3. Research objectives

The primary research objective was to characterize ambient concentrations of $PM_{2.5}$ pollution over space and time in Grenada and Carriacou between January 6, 2020 and October 31, 2020. This objective included assessing the impacts of North African desert dust events on ambient concentrations of $PM_{2.5}$.

The secondary objective of this thesis was to investigate whether public health measures, implemented in Grenada to slow the spread of SARS-CoV-2, reduced ambient concentrations of $PM_{2.5}$.

4. Methods

4.1 Study Design and Variables

This was an exposure-based study that collected data from low-cost air pollution sensors in Grenada. These data were supplemented with meteorological data, and information on public health interventions to reduce the spread of COVID-19. The data were summarized on a daily basis, and they are described in this section.

4.1.1. Ambient PM Pollution Data

Ambient PM pollution data were collected from five fixed-site PurpleAir PA-II-SD monitors.[235] Four of these monitors were installed at different locations across Grenada, and one on Carriacou (Figure 3). For Grenada, two monitors were installed at homes of collaborators on this project who are faculty members at St. George's University. One was installed on the roof of a two-storey house on the southern edge of the island (Egmont), while the other on the roof of a house on the northeastern edge of the island (Bathway). Another monitor was also installed at ground-level on the tarmac of the Maurice Bishop International Airport on the southwestern edge of the island (Airport). The fourth monitor was installed on the roof of the Ministerial complex in St. George's (Tempe). On Carriacou, the one monitor was installed on the upper wall on the outside of a house on the northeastern edge of the island (Windward).

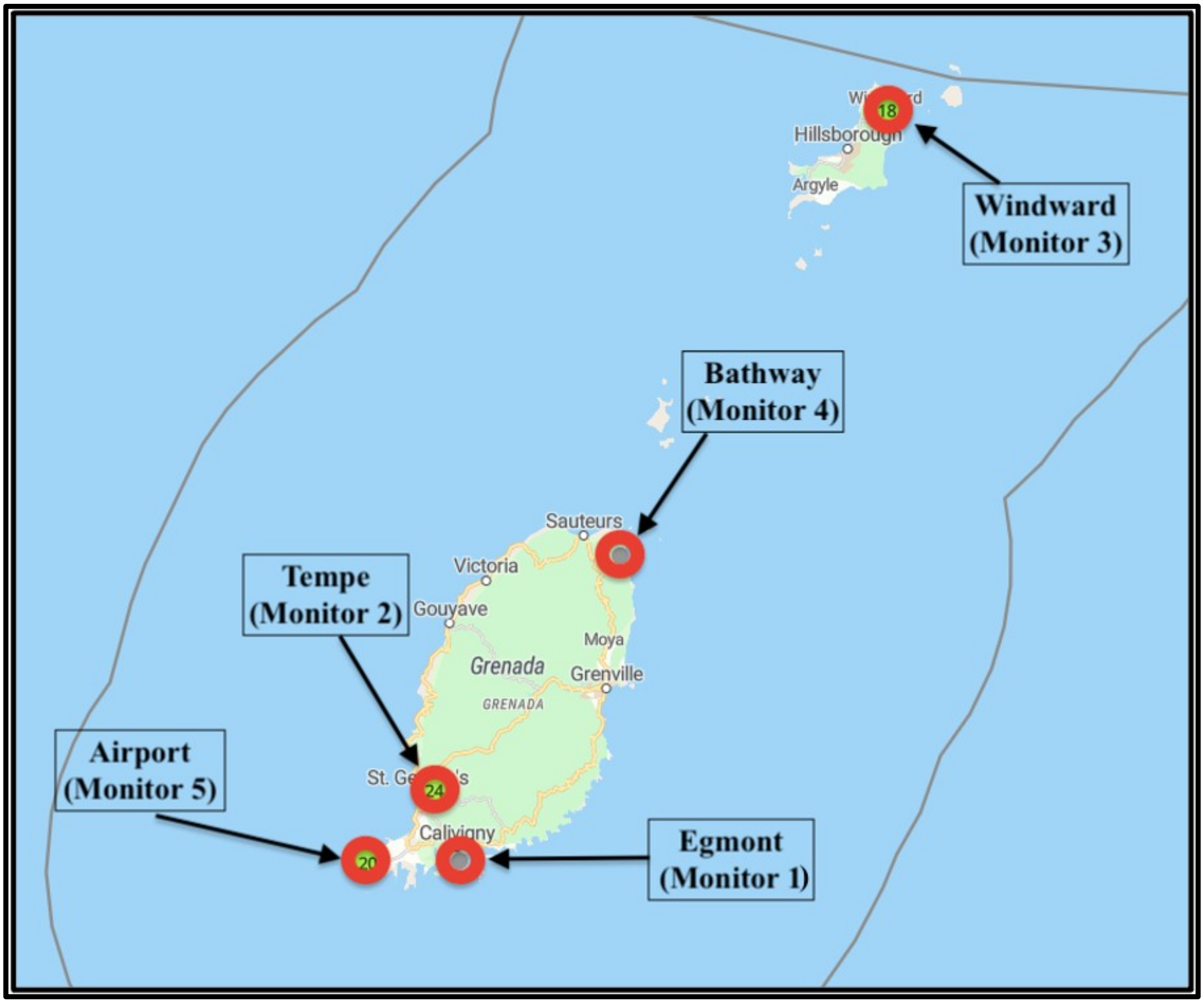

***Figure 3**: Geographical locations of the five PurpleAir monitors that were installed in Grenada.*

The PA-II-SD monitor collects continuous measures of real-time mass concentrations of PM_1, $PM_{2.5}$, and PM_{10}. They rely on laser counters to estimate PM in real time. Within the monitor, a fan draws in a sample of air past a laser beam and any particles present within the air reflect some light from the laser beam onto a detection plate. The reflection of light is measured as a pulse by the detection plate. The length of the pulse determines the size of the particle and the number of pulses determines the particle count. The mass concentrations of PM_1, $PM_{2.5}$, and PM_{10} are then calculated from these particle counts. Each PA-II-SD monitor has two laser channels which produces two independent measurements of PM_1, $PM_{2.5}$, and PM_{10}.[236]

PurpleAir stationary monitors are widely used instruments for air quality monitoring across the world and correlate reasonably well with higher quality monitoring devices.[237,238] In Greek cities Athens and Ioannina, several PurpleAir PA-II-SD monitors measured hourly $PM_{2.5}$ concentrations and were compared against two types of reference grade monitors over five month periods (summer 2019 and winter/spring 2020 in Athens, winter/spring 2019-2020 in Ioannina).[237] PurpleAir hourly measurements showed strong correlation with a beta attenuation monitor ($R^2 = 0.87$) installed in Athens, and with an optical reference grade monitor ($R^2 = 0.98$) installed in Ioannina. In Riverside, California, hourly $PM_{2.5}$ concentrations measured from twelve low-cost triplicates (groups of 3) were compared against a reference grade monitor over the course of February 2015 to March 2018.[239] Low-cost sensor triplicates were compared against the reference grade monitor in ambient conditions, typically for 8-week periods at a time. The PurpleAir triplicate was strongly correlated with the reference grade monitor, with an R^2 value of 0.95 for each of the monitors. As well, the Plantower PMS sensor that forms the basis of the PurpleAir monitor has shown good correlations with reference grade monitors.[240–242]

4.1.2. Meteorological Data

Hourly meteorological data for precipitation, relative humidity, atmospheric pressure, temperature, wind speed, and visibility were collected by Grenada's meteorological office.[243] This monitoring was done at the Maurice Bishop International

Airport. Hourly data were used to construct daily summaries that were used in data analyses.

4.1.3. North African Desert Dust Episodes

Each day between January 6 and October 31, 2020 was classified as a NADD day or not. The classification was done by using a composite method. This method used the US Naval Research Laboratory's NAAPS Global Aerosol Model,[244] daily mean visibility measures from the airport, and Modern-Era Retrospective Analysis for Research and Applications Version 2 (MERRA-2) derived dust aerosol optical thickness maps.[245] Naval Research Laboratory's NAAPS is an aerosol forecast model that produces images of dust surface concentration (as well as total optical depth, sulphate surface concentration, and smoke surface concentration) around the world, up to 6 days in advance at 6-hour intervals. NAAPS is helpful in identifying NADD days retrospectively because forecast images can be looked at from archives back to March of 2000.[178] MERRA-2 is a NASA atmospheric reanalysis (a systematic approach to produce datasets for climate monitoring and research) that assimilates space-based observations of aerosols and represents their interactions with other physical processes within Earth's climate system.[245,246]

To identify NADD days, NAAPS forecast images for dust surface concentration in the Caribbean region were viewed at 6-hour intervals each day from the beginning of the study period (January 6, 2020) to the end of the study period (October 31, 2020). Dust surface concentration (or dust mass mixing ratio at the surface; $\mu g/m^3$) in these forecast images begin at a contour of 20-40 $\mu g/m^3$ and doubles each successive contour (40-80, 80-160, 160-320, 320-640, etc.). Each day during the study period that had at least one 6-hour interval having a dust surface concentration of 20+ $\mu g/m^3$ forecasted over Grenada would be designated a potential NADD day. Next, all potential NADD days would be examined for the reported daily mean visibility. If these days had a daily mean visibility of 15 km or less, it was considered a potential NADD day, while days with a daily mean visibility over 15 km were considered a non-NADD day. A threshold of ≤15 km was applied as this is the benchmark used by the Trinidadian meteorological office.[175] Finally, MERRA-2 dust aerosol optical thickness images were examined to validate each potential NADD day. If there was a clear presence of dust aerosols over Grenada on these potential NADD days (accounting for NAAPS forecasted dust surface concentration and daily mean visibility), they would be classified as NADD days. Days that weren't considered potential NADD days but had a daily mean visibility of ≤15 km were also viewed for the presence of dust.

4.1.4. Public Health Measures to reduce spread of COVID-19 in Grenada

The government of Grenada implemented a series of public health restrictions from March 2020 onwards to reduce the spread of SARS-CoV-2. Restrictions were classified into physical distancing measures and business or travel restrictions. A description of these restrictions and the calendar period for which they were adopted are described below.

Physical Distancing Practices

Information in daily newspapers ("NOW Grenada"[247] and the Barbados newspaper "Loop News Barbados"[248]), were used to construct daily measures of physical distancing regulations. These included daily curfew (designated time periods of curfew/movement and hours of curfew/movement per day) and social gathering limit measures (social gathering limits not including weddings or funerals, social gathering limits for only weddings, and social gathering limits for only funerals).

Restrictions on Travel

In late March 2020, Grenada closed its international airport to all commercial passenger traffic.[213] As the incoming and outgoing commercial flights drastically decreased, data were compiled to assess whether there was an association with air quality.[249] Daily data on commercial airplane arrivals and departures for Grenada's Maurice Bishop International Airport were extracted from "FlightStats".[250] In late March 2020, restrictions were also placed on cruise ships, pleasure craft, and live-aboard vessels resulting in decreased number of these vessels in Grenada's ports.[211,212] Daily data on arrivals and departures to Grenada's ports were provided by the Marine Department of Grenada's Port Authorities.[251] A description of all the travel related variables that were evaluated are described below.

Table 3: *Travel restriction related variables used in analyses.*

Public health intervention measure considered in analysis	Functional form of variable
Social Gatherings Limits	Yes or No Count
Commercial Airplane Movements	Count
Ship Movements	Count

4.2 Statistical Analysis

4.2.1. Temporal Changes in Ambient $PM_{2.5}$

Hourly mean ambient $PM_{2.5}$ values measured from installed monitors were downloaded from the PurpleAir website,[252] and from these, daily and monthly summary measures were constructed. Daily mean concentrations of ambient $PM_{2.5}$ were included if they had at least 16 hours of data collection for that day. An analysis of variance test was used to determine whether there were differences in the concentrations of $PM_{2.5}$ across different days of the week.

Monthly mean values of temperature, precipitation, relative humidity, atmospheric pressure, wind speed and visibility were calculated using daily mean values reported from the meteorological office at the Maurice Bishop International airport. Using RStudio,[253] scatterplots were created and Pearson correlation coefficient values were estimated for daily measures of $PM_{2.5}$, temperature, precipitation, relative humidity, atmospheric pressure, wind speed and visibility.

4.2.2. Contrasting $PM_{2.5}$ between NADD and Non-NADD days

The frequency distribution of $PM_{2.5}$ concentrations on NADD and non-NADD days were summarized and compared using boxplots. An independent two-group Student's *t*-test was used to compare the mean daily $PM_{2.5}$ on NADD days compared to non-NADD days.[254]

4.2.3. Estimating the Impact of COVID-19 on Ambient Concentrations of $PM_{2.5}$

Impacts of COVID-19 restrictions on ambient concentrations of $PM_{2.5}$ were evaluated using multivariable regression. As a first step, all data were entered into an analysis file that contained one observation for each calendar day. These data included daily measures of meteorological variables, curfew hours per day, types of curfew days, social gathering limits (not including wedding or funeral, only wedding limits, and only funeral limits), presence of Emergency Powers/Public Health Act, presence of NADD days, as well as daily commercial airplane and boat/ship movements. Each of the potential explanatory variables were examined using a combination of descriptive statistics and fitting separate regression models for each variable with ambient concentrations of $PM_{2.5}$ averaged from all five monitors, and ambient concentrations of $PM_{2.5}$ averaged from the four Grenada located monitors. Ambient $PM_{2.5}$ data from the four Grenada monitors were averaged to compare them with COVID-19 public health measures that were specific to Grenada, slightly different from those enforced on Carriacou. Variables that were associated with daily ambient $PM_{2.5}$ in a bivariate model were entered into a multiple regression model to collectively best predict daily ambient $PM_{2.5}$. Separate multiple regression models were constructed to best predict daily ambient

$PM_{2.5}$ averaged across all five monitors and daily ambient $PM_{2.5}$ averaged from the four Grenada located monitors.

Daily mean $PM_{2.5}$ concentrations in Grenada measured from installed monitors during 2020 and 2021 were also examined together. This is because there are no other long-term daily measures of ambient $PM_{2.5}$ in Grenada before 2020. Ambient $PM_{2.5}$ data from 2021 would provide additional information about seasonal patterns to help contextualize trends observed in this study throughout COVID-19 in 2020. Thus, a line graph was constructed to compare daily mean $PM_{2.5}$ concentrations at the same urban location (Tempe) in Grenada during the time period of January to beginning of April, in 2020 and 2021.

5. Results

5.1. Temporal Changes in $PM_{2.5}$

5.1.1. Daily Changes in $PM_{2.5}$

Figure 4 demonstrates daily mean $PM_{2.5}$ concentrations measured for the five PurpleAir monitors in Grenada and Carriacou from January 7 to October 31, 2020. For 281 of the 299 days (~94%) during this period, the daily mean $PM_{2.5}$ concentrations were less than 10 $\mu g/m^3$. The overall mean exposure during the study period was 4.48 $\mu g/m^3$, which is lower than the annual WHO guideline of 10 $\mu g/m^3$. Most spikes in the daily mean $PM_{2.5}$ occurred during NADD events. These events mostly occurred from late January to late February, and from early May to mid-July during the study period. Trends in daily mean $PM_{2.5}$ were mostly synchronous amongst the five monitors during the study period.

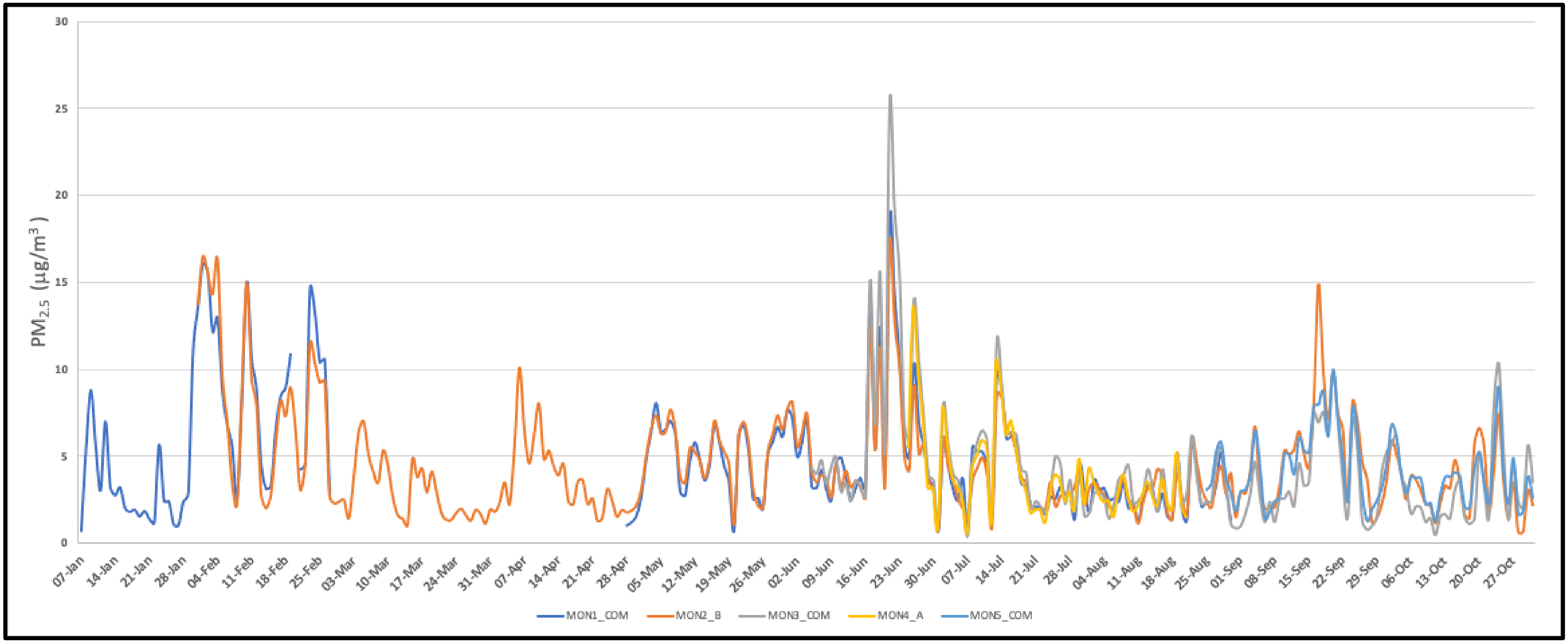

Figure 4*: Daily mean PM*$_{2.5}$ *concentrations for each of the five PurpleAir monitors installed in Grenada and Carriacou from January 7 to October 31, 2020.*

5.1.2. Variations in $PM_{2.5}$ by Month, Day of Week, and Time of Day

Variations in the frequency distributions of daily mean $PM_{2.5}$ concentrations by month are presented in Figure 5.[2] A statistically significant difference in daily mean $PM_{2.5}$ by month ($p<0.001$) was found.[3] The highest monthly mean $PM_{2.5}$ values were observed in February (8.06 $\mu g/m^3$) and June (6.61 $\mu g/m^3$). Months with submaximal monthly mean $PM_{2.5}$ concentrations include May (5.16 $\mu g/m^3$) and September (4.52 $\mu g/m^3$). Tabular data for monthly $PM_{2.5}$ concentrations are provided in Table C8 in Appendix C.

[2] Empty circles are outliers, solid circles are means, and solid horizontal lines are medians.

[3] Test of significance from an ANOVA model found that there were statistically significant differences in the monthly means ($p<0.001$).

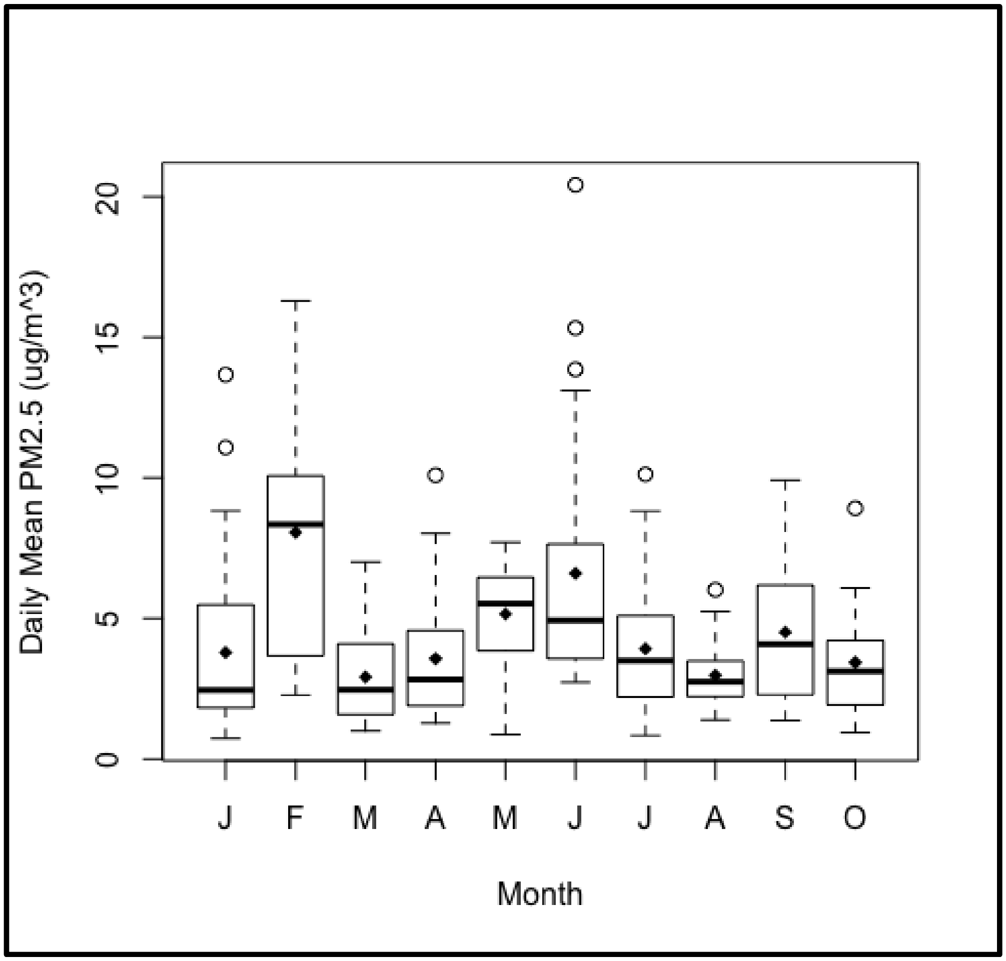

Figure 5*: Frequency distribution of daily mean $PM_{2.5}$ concentrations, by month, January to October 2020.*

Figure 6 provides a graphical representation of $PM_{2.5}$ concentrations by day of week. The highest daily mean concentrations of $PM_{2.5}$ were observed on Thursdays (4.62 $\mu g/m^3$) and Fridays (4.80 $\mu g/m^3$). However, there were no statistically significant differences in the mean concentrations across the seven days of the week (p-value = 0.90).[4] These tabular data are provided in Table C9 in Appendix C.

[4] Test of significance from an ANOVA model found that there were not statistically significant differences in the daily means on a day of week basis (p = 0.90).

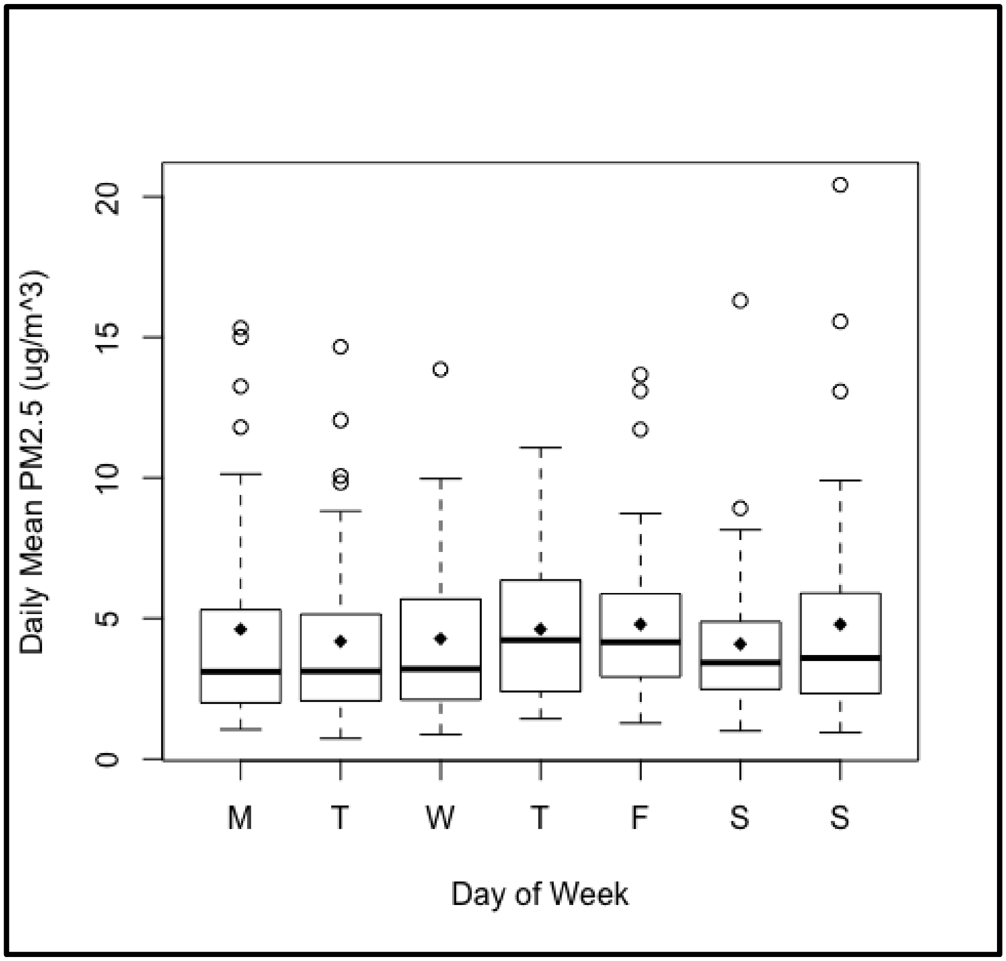

Figure 6*: Frequency distribution of daily $PM_{2.5}$ concentrations by day of the week, based on daily mean $PM_{2.5}$ concentrations between January 7 and October 31, 2020.*

Boxplots were created to describe the differences in $PM_{2.5}$ concentrations measured in a rural setting (Egmont) and an urban setting (Tempe) in Grenada. These boxplots are shown in Figure 7. Hourly measures taken at the urban location were consistently higher than the rural location ($p<0.001$),[5] however, the differences were largest between 3:00 PM and 9:59 PM.

[5] Student's *t*-test results demonstrate a statistically significant difference in hourly $PM_{2.5}$ between the urban (Tempe) and rural (Egmont) locations ($p<0.001$).

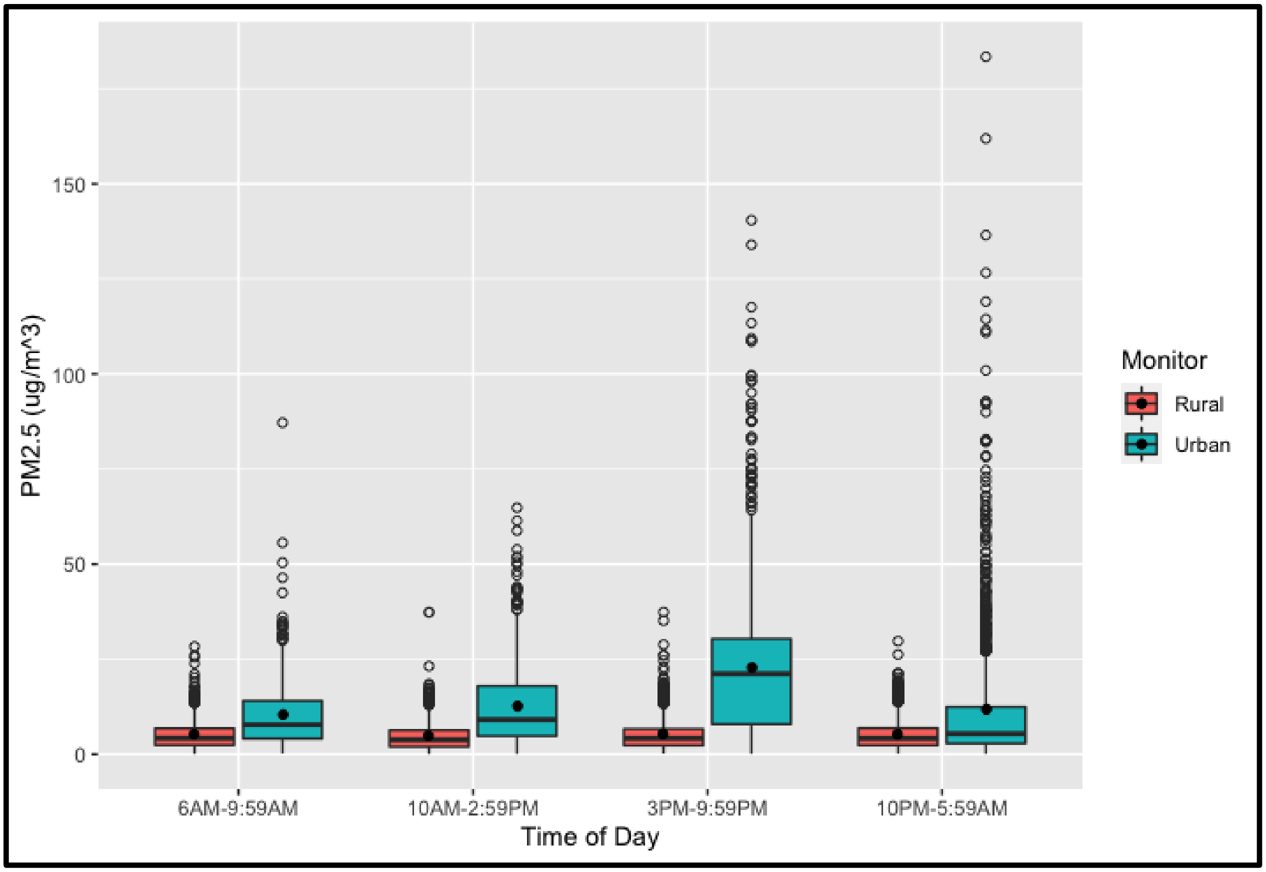

***Figure** 7: Boxplot comparison of hourly $PM_{2.5}$ concentrations at a rural location (orange) and an urban location (blue), by time of day. Time period of data: January 31 to February 28, 2020 and April 27 to August 31, 2020.*

5.1.5. Daily Mean $PM_{2.5}$ and Daily Meteorological Measures

Scatterplots of daily mean $PM_{2.5}$ concentrations and daily measures of meteorological variables are provided in Figure 8. Meteorological variables with the strongest linear association with daily mean $PM_{2.5}$ concentrations were visibility (r = -0.63), wind speed (r = 0.26), and atmospheric pressure (r = 0.22).

Descriptive statistics of daily meteorological measures are shown for NADD days and non-NADD days (Table 4). The daily mean visibility on NADD days (13.27 km) is lower than the same measure on non-NADD days (20.66 km). Also, mean daily mean wind speed is higher on NADD days (6.74 m/s) than on non-NADD days (5.54 m/s). Monthly mean values of meteorological variables and ambient $PM_{2.5}$ are provided in Table D11 in Appendix D.

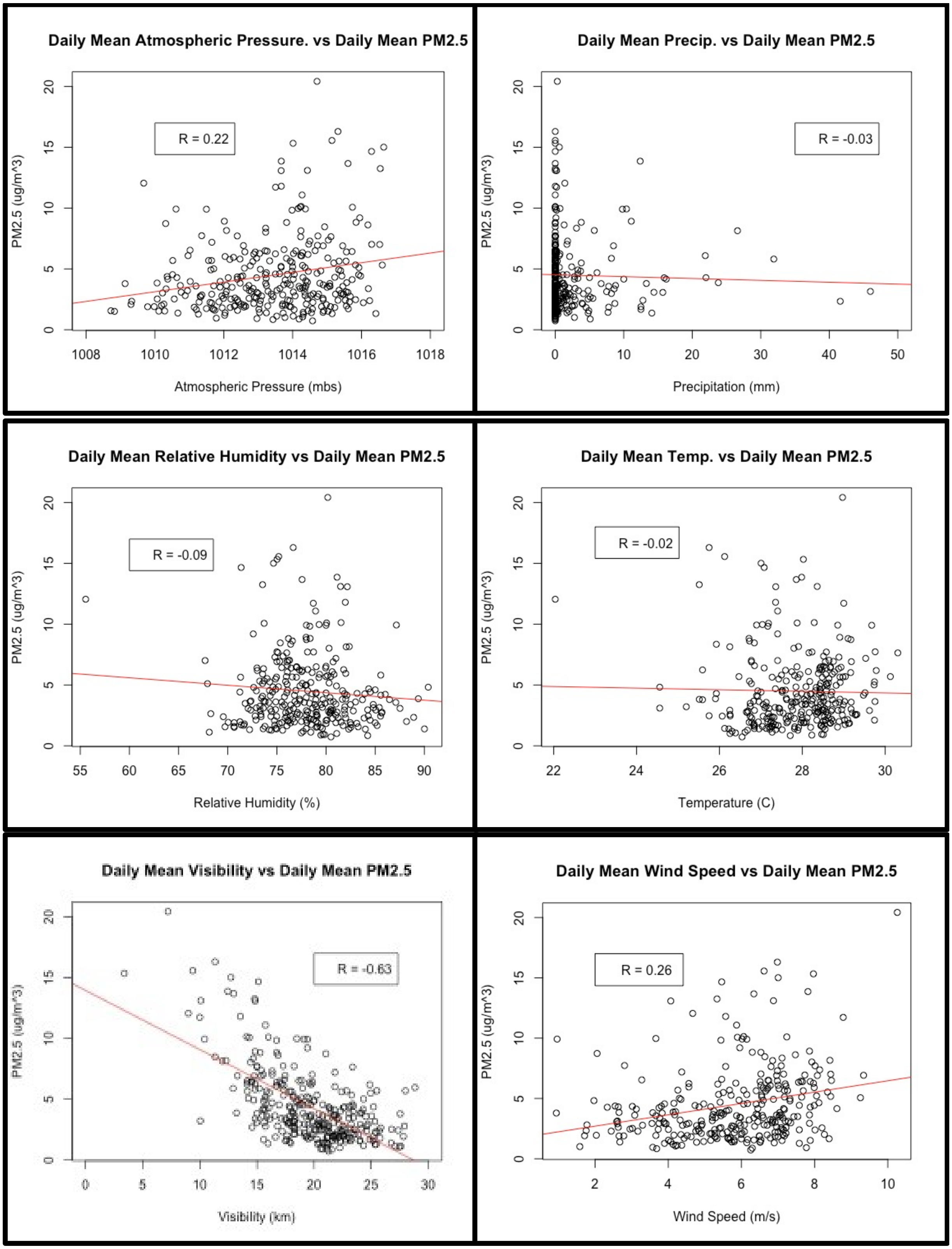

***Figure 8**: Scatterplots of daily mean $PM_{2.5}$ concentrations select meteorological characteristics, January 7 to October 31, 2020.*

Table 4: *Descriptive statistics of daily meteorological measures during NADD days and Non-NADD Days.*

Daily mean environmental variable	Mean	SD	Min.	1st Quartile	Median	3rd Quartile	Max.
NADD Day (48 days)							
Visibility (km)	13.27	2.52	3.38	12.42	14.21	14.83	17.38
Wind Speed (m/s)	6.74	1.42	4.07	5.73	6.80	7.83	10.26
Atmospheric Pressure (mbs)	1014	1.47	1010	1013	1014	1015	1017
Relative Humidity (%)	78.29	5.14	55.55	75.59	77.76	81.21	89.38
Precipitation (mm)	3.57	7.26	0.00	0.00	0.20	3.33	31.90
Temperature (Celsius)	27.55	1.35	22.04	26.88	27.93	28.56	29.18
Non-NADD Day (257 days)							
Visibility (km)	20.66	3.06	15.00	18.25	20.58	22.62	28.83
Wind Speed (m/s)	5.54	1.71	0.94	4.30	5.80	6.92	8.61
Atmospheric Pressure (mbs)	1013	1.72	1009	1012	1014	1015	1017
Relative Humidity (%)	77.97	4.20	67.70	74.87	78.00	80.49	90.40
Precipitation (mm)	1.96	5.14	0.00	0.00	0.00	1.70	46.00
Temperature (Celsius)	27.90	0.99	24.56	27.18	27.99	28.58	30.30

5.2. NADD and $PM_{2.5}$ Concentrations

Figure 9 displays a boxplot comparison of daily mean $PM_{2.5}$ concentrations during NADD days and non-NADD days. The mean of daily mean $PM_{2.5}$ concentrations on NADD days was nearly 2.5 times higher than on non-NADD days (8.9 vs 3.6 µg/m^3; $p<0.001$).[6] The tabular data for $PM_{2.5}$ concentrations on NADD days and non-NADD days are displayed in Table C10 in Appendix C.

[6] Student's *t*-test results demonstrate a statistically significant difference between daily mean $PM_{2.5}$ on NADD days and non-NADD days ($p<0.001$).

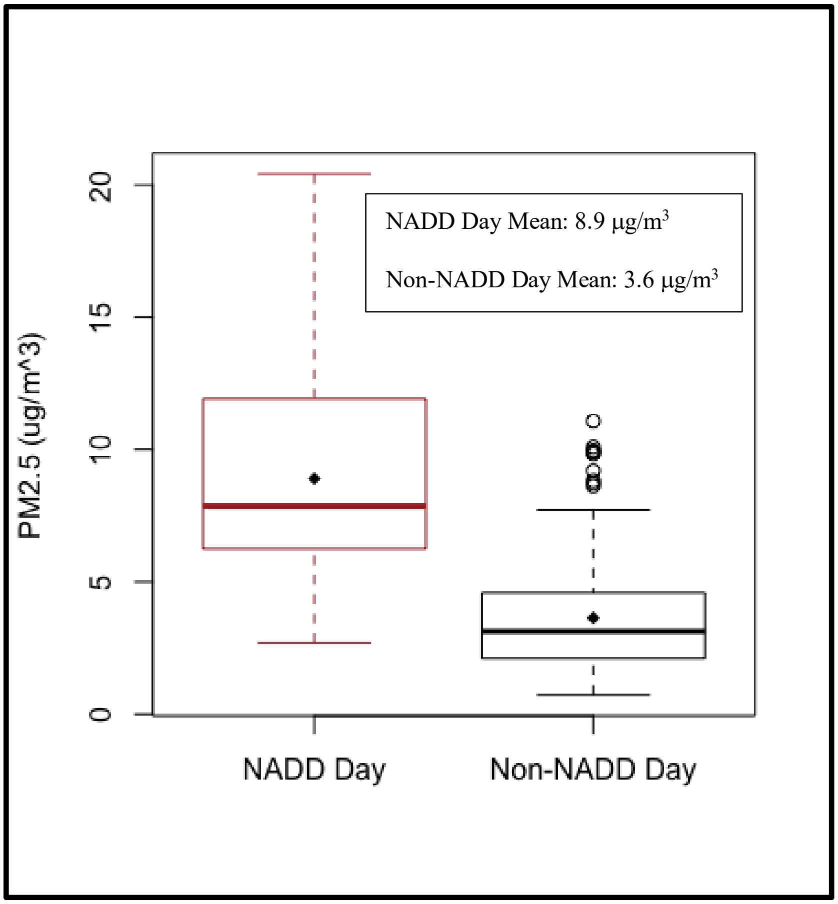

Figure 9*: A boxplot comparison of daily mean $PM_{2.5}$ concentrations on North African Desert Dust days and non-desert dust days in Grenada and Carriacou from January 7 to October 31, 2020.*

5.3. COVID and Air Quality

Descriptive statistics and regression results of various potential predictor variables (meteorological factors, NADD days, public health intervention measures) for daily mean $PM_{2.5}$ concentrations averaged across the 5 installed monitors are displayed in Table 5. Similar data averaged across the four monitors, excluding Carriacou, are shown in Table E12 of Appendix E.

Predictor variables found that were associated with $PM_{2.5}$ in simple regressions included: daily mean atmospheric pressure, daily mean wind speed, NADD days, and emergency powers (i.e., public health act measures). Summary output results of the multiple regression model that best explains daily mean $PM_{2.5}$ concentrations averaged across the 5 installed monitors are shown in Table 6. According to the multiple regression model: the presence of emergency powers on a given day was associated with a 0.52 $\mu g/m^3$ decrease in daily mean $PM_{2.5}$, the occurrence of a NADD day was associated with a 4.93 $\mu g/m^3$ increase in daily mean $PM_{2.5}$, an increase of 1 m/s in daily mean wind speed was associated with a 0.09 $\mu g/m^3$ increase in daily mean $PM_{2.5}$, and an increase of 1 millibar (mbs) in daily mean atmospheric pressure was associated with 0.12 $\mu g/m^3$ increase in daily mean $PM_{2.5}$. This multiple regression model had a reasonable fit and was able to account for about 40% (Adjusted R-squared = 0.40) of the variance in daily mean $PM_{2.5}$ averaged across the 5 monitors.

Similar output for the four monitors, excluding Carriacou, are also provided in Table 6. According to the multiple regression model: the presence of emergency powers on a given day was associated with a 0.51 $\mu g/m^3$ decrease in daily mean $PM_{2.5}$, the occurrence of a NADD day was associated with a 4.66 $\mu g/m^3$ increase in daily mean $PM_{2.5}$, an increase of 1 m/s in daily mean wind speed was associated with a 0.05 $\mu g/m^3$ increase in daily mean $PM_{2.5}$, and an increase of 1 mbs in daily mean atmospheric pressure was associated with a 0.12 $\mu g/m^3$ increase in daily mean $PM_{2.5}$. This multiple regression model predicts about 37% (Adjusted R-squared = 0.37) of the variance in daily mean $PM_{2.5}$ averaged across the 4 Grenada monitors.

In Figure 10, 3-day rolling mean $PM_{2.5}$ concentrations measured from the urban located monitor in Grenada from January to April in 2020 and 2021 are compared in a line graph. Daily mean $PM_{2.5}$ concentrations for this figure did not require adhering to the

16-hour mean inclusion-criteria as there was already a dearth of daily mean values to compare for 2020 and 2021. This figure suggests that daily mean $PM_{2.5}$ slightly declines from January to April as it occurred in 2020 and 2021 at the same monitor location.

***Table 5**: Descriptive statistics and simple regression results from comparing each characteristic variable with daily $PM_{2.5}$ averaged from each of the five PurpleAir monitors in Grenada and Carriacou from January 7 to October 31, 2020.*

Characteristic	Days	Mean $PM_{2.5}$ (Std Dev)	Model P-Value[7]
Daily boat/ship movements			0.26
0-4	193	4.36 (2.97)	
5-10	102	4.57 (3.24)	
11-16	10	5.99 (4.44)	
			0.16
0-2 (Quartile 1)	108	4.56 (2.72)	
3-4 (Quartile 2)	85	4.11 (3.25)	
5-6 (Quartile 3)	52	4.14 (3.07)	
7-16 (Quartile 4)	60	5.23 (3.58)	
Daily airplane movements			<0.001
0-9	222	4.20 (2.69)	
10-19	60	5.84 (4.16)	
20-28	23	3.74 (3.19)	
			0.03
0-2 (Quartile 1)	163	4.45 (2.90)	
3-14 (Quartile 2)	70	3.84 (2.34)	
15-28 (Quartile 3)	72	6.96 (4.07)	
Present of Emergency Powers			0.02
No	85	5.19 (4.02)	
Yes	220	4.32 (2.68)	
Curfew Hours			0.07
None	200	4.34 (3.07)	
Less than 12	73	5.16 (3.48)	
12 – 24	32	3.85 (2.18)	
NADD Day			<0.001
Yes	48	8.90 (4.02)	
No	257	3.64 (2.01)	
Daily Temperature (Celsius)			0.31
22.00-27.20 (Quartile 1)	79	4.67 (3.80)	
27.21-28.00 (Quartile 2)	74	3.19 (3.12)	
28.01-28.60 (Quartile 3)	76	4.06 (2.50)	
28.61-30.30 (Quartile 4)	76	4.93 (2.91)	
Daily Atmospheric Pressure (mbs)			0.02
1009.00-1012.00 (Quartile 1)	77	3.69 (2.34)	
1012.01-1014.00 (Quartile 2)	76	4.30 (2.69)	
1014.01-1015.00 (Quartile 3)	76	4.86 (3.55)	
1015.01-1017.00 (Quartile 4)	76	5.12 (3.59)	
Daily Wind Speed (m/s)			0.002
0.94-4.56 (Quartile 1)	79	3.55 (2.26)	

[7] P-values derived from simple regression model p-values of each characteristic variable and daily mean $PM_{2.5}$.

4.57-5.98 (Quartile 2)	74	4.08 (3.01)	
5.99-7.00 (Quartile 3)	78	4.94 (3.49)	
7.01-10.30 (Quartile 4)	74	5.33 (3.28)	
Social Gathering Limits (not including Weddings or Funerals)			<0.001
No Social Gathering Limits	84	5.23 (4.03)	
20 people	124	3.71 (2.01)	
0 people	97	4.88 (3.24)	

***Table 6**: Summary output results from a multiple regression model to best explain daily mean $PM_{2.5}$ averaged from all 5 installed monitors, and daily mean $PM_{2.5}$ averaged from all 4 monitors installed on Grenada.*

Based on 5 monitors

Daily Mean Composite $PM_{2.5}$ = -117.66 – 0.52(Presence of Public Health Act Measures(Yes)) + 4.93(NADD Day(Yes)) + 0.09(Daily Mean Wind Speed) + 0.12(Daily Mean Atmospheric Pressure)

Variables[8]	Beta-Coefficient	Pr(> | t |)
Y-intercept	-117.66	0.24
Presence of Public Health Act Measures (Yes vs No)	-0.52	0.16
NADD Day (Yes vs No)	4.93	<0.001
Daily Mean Wind Speed (m/s)	0.09	0.05
Daily Mean Atmospheric Pressure (mbs)	0.12	0.23

Based on 4 monitors

Daily Mean Composite $PM_{2.5}$ = -119.46 – 0.51(Presence of Public Health Act Measures(Yes)) + 4.66(NADD Day (Yes)) + 0.05(Daily Mean Wind Speed) + 0.12(Daily Mean Atmospheric Pressure)

Y-intercept	-119.46	0.23
Presence of Public Health Act Measures (Yes vs No)	-0.51	0.16
NADD Day (Yes vs No)	4.66	<0.001

[8] All variables associated with daily mean $PM_{2.5}$ in Table 5 were considered for this multivariable regression model.

Daily Mean Wind Speed (m/s)	0.05	0.26
Daily Mean Atmospheric Pressure (mbs)	0.12	0.22

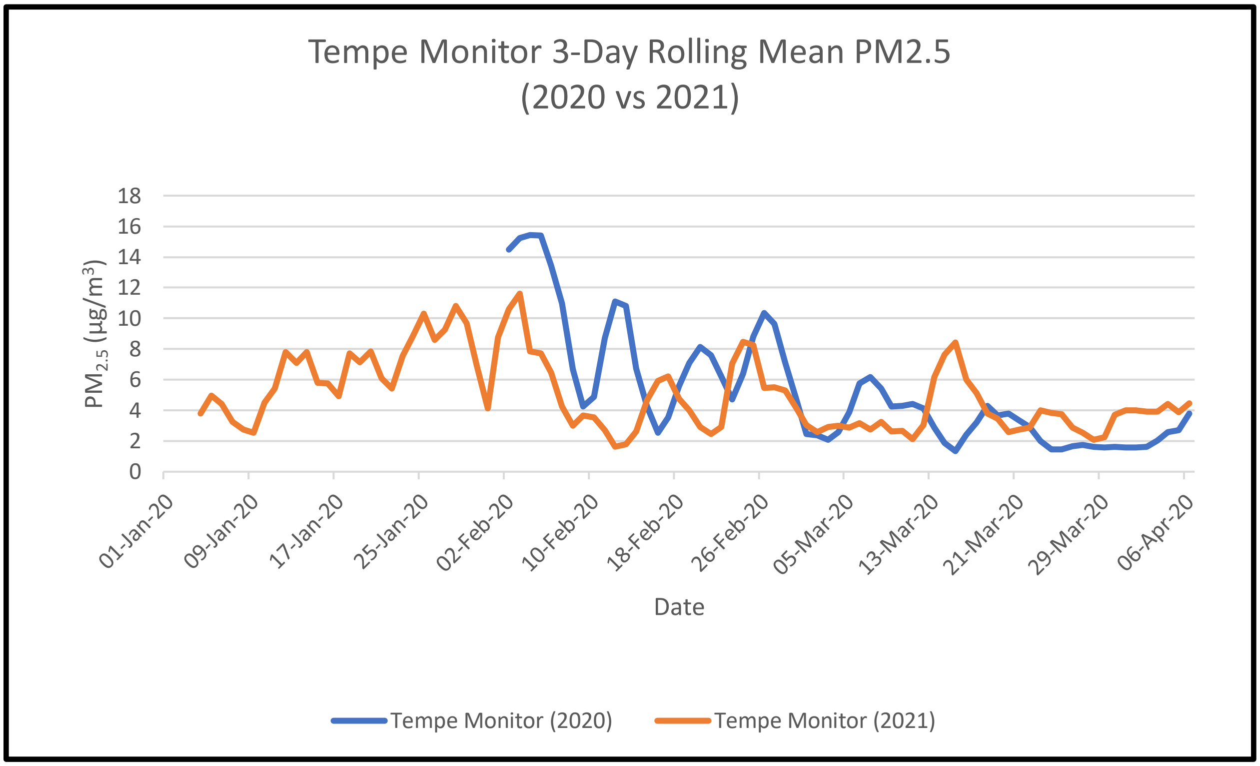

***Figure 10**: A line graph of 3-day rolling mean $PM_{2.5}$ concentrations measured from the Tempe monitor in an urban area near Grenada's capital city, from January 4 to April 6, 2020 (blue) and February 2 to April 6, 2021 (orange).*

6. Discussion

In this thesis, the first results of an air pollution monitoring campaign that provided continuous monitoring of ambient fine particulate matter in Grenada for 2020 are provided. Overall, ambient concentrations in Grenada were low relative to other countries,[255] with a daily average of 4.48 μg/m^3 observed between January 6 and October 31, 2020. For example, the annual average in the highest polluted country, Nepal, was 99.47 μg/m^3, in 2017, while the corresponding value for Canada was 6.43 μg/m^3.[2,256,257] Another important observation was that the daily mean averages tended to exhibit relatively little variability, apart from spikes in daily mean $PM_{2.5}$ due to NADD episodes. The magnitude of these increases was similar to other island nations that also experience dust events.[177,258,259]

Overall, the general implementation of public health measures in Grenada was found to be associated with a modest decrease (~12%) in daily mean $PM_{2.5}$. Somewhat greater reductions in ambient $PM_{2.5}$ during the COVID-19 pandemic have been reported elsewhere. For example, locked-down cities in China observed a 24% decrease in ambient $PM_{2.5}$ during the two month lockdown period relative to the same period in 2019,[197] while across 22 cities in India, there was a 43% decrease in ambient $PM_{2.5}$ during a month long lockdown period compared to the same period from 2017-2019.[200] While decreases in $PM_{2.5}$ have been observed during the pandemic, even greater reductions would be expected for NO_2 given it is a marker for traffic related pollution. This finding has been borne out in some reports. Unfortunately, monitoring data are not available for NO_2 in Grenada or Carriacou. Though, this represents a pollutant for which future monitoring should be considered.

Specific public health measures such as social gathering limits and curfews were not associated with reductions in the daily mean $PM_{2.5}$. Meaningful associations were also not found between air and boat/ship travel restrictions and daily mean $PM_{2.5}$. However, it is possible that if there was a more localized impact of these travel restrictions on ambient $PM_{2.5}$, the monitors used were too far away to capture it. Furthermore, the ability to detect very small changes in source-specific (e.g., boats, planes, etc.) concentrations of $PM_{2.5}$ using low-cost monitors would be difficult due to the already low ambient concentrations of $PM_{2.5}$ in Grenada. For these reasons, this exposure study is likely better capable of detecting cumulative impacts from all sources on $PM_{2.5}$ than impacts from any one source.

6.1. Temporal Trends in Ambient $PM_{2.5}$ Concentrations

6.1.1. Daily Changes in Ambient $PM_{2.5}$

As previously mentioned, concentrations of ambient $PM_{2.5}$ for Grenada were low. The WHO standard for daily mean concentration of $PM_{2.5}$, specifically, 25 $\mu g/m^3$, was only exceeded once during the study period, and this occurred during the June 2020 'Godzilla' dust storm.[124]

This study's estimate of an annual average $PM_{2.5}$ concentration (based on the average of daily means) for Grenada in 2020 was 4.48 $\mu g/m^3$, a value that is below the WHO's annual standard for $PM_{2.5}$ of 10 $\mu g/m^3$.[124] This estimate for Grenada is lower than with findings based on long-term ground-level measurements and satellite observations of ambient $PM_{2.5}$ in the Caribbean.[177,258,259] In Guadeloupe, Cadelis et al. (2014) found an average daily ambient $PM_{2.5}$ concentration of 9.6 $\mu g/m^3$ measured from January 11 to

December 31, 2011.[177] In Puerto Rico, average annual concentrations of $PM_{2.5}$ from 2000 to 2003 in the cities of Guayanabo (urban) and Fajardo (rural) were 11.6 and 8.5 $\mu g/m^3$, respectively.[259] Using satellite observations, from 2001-2010, the population-weighted mean (+/- Standard Deviation) ambient $PM_{2.5}$ concentration for the Caribbean was estimated to be 7.0 +/- 2.5 $\mu g/m^3$.[258] Differences between Grenada and these other findings may be due to a number of factors including locally based sources of pollution, meteorology, and temporal (i.e., year by year) variations in concentration levels. It is also possible that differences in the methodologies for estimating concentrations of $PM_{2.5}$ (PurpleAir vs satellite) have contributed to some of these differences.

In the past, there has been little monitoring of air pollution in the Caribbean. This has changed somewhat, as of September 2021, there are air pollution monitors in the Bahamas (two low-cost sensors), Puerto Rico (twelve low-cost sensors, 1 reference grade sensor), British Virgin Islands (three low-cost sensors), US Virgin Islands (one low-cost sensor), Martinique (three reference grade sensors), Grenada (two low-cost sensors), Trinidad (three low-cost sensors), and Curacao (one reference grade sensor).[260] Each of the low-cost sensors installed in each Caribbean nation also happens to be a PurpleAir sensor.[261]

6.1.2. North African Desert Dust and Daily Changes in Ambient $PM_{2.5}$

Daily mean $PM_{2.5}$ during NADD days in Grenada (8.9 $\mu g/m^3$) were nearly 2.5 times higher than the daily mean on non-NADD days (3.6 $\mu g/m^3$). Days of higher daily mean $PM_{2.5}$ in Grenada, typically around 15-20 $\mu g/m^3$, mostly occurred during NADD episodes. Aside from these dust episodes, daily ambient $PM_{2.5}$ in Grenada is fairly low, likely due to the relatively small population, lack of major industrialization and motor vehicle traffic on the island, as well as consistent air flow from trade winds that disperses any particulate pollution. In addition, unlike countries in the Northern Hemisphere that have higher pollution levels in the winter, Grenada has relatively constant warmer temperatures, and thus does not have sources of air pollution from the heating of homes.

Over prolonged periods of time, other studies have also found NADD intrusions to be responsible for large increases in ambient $PM_{2.5}$ in island settings. In Guadeloupe, across 52 NADD days, the average daily $PM_{2.5}$ concentration was 14.4 +/- 10.5 $\mu g/m^3$ and across 285 non-NADD days, the average daily $PM_{2.5}$ concentration was 8.8 +/- 2.4 $\mu g/m^3$.[177] In Palermo, the capital city of the Italian island Sicily, 40 daily samples of ambient $PM_{2.5}$ were measured during NADD episodes and normal (no desert dust) conditions, between November 2008 to February 2009.[262] Average $PM_{2.5}$ during normal conditions and 4 NADD episodes were measured as 29 +/- 6 $\mu g/m^3$ and 78 +/- 28 $\mu g/m^3$, respectively. Off the northwestern coast of Africa in the Canary islands, average ambient $PM_{2.5}$ concentrations were measured on NADD days and non-NADD days, from 2004 to 2009.[263] Average $PM_{2.5}$ from 491 NADD days and 1701 non-NADD days were measured as 23.45 and 11.50 $\mu g/m^3$, respectively.

As discussed above, ambient $PM_{2.5}$ concentrations on NADD days in Grenada were lower than nearby islands also impacted by these dust episodes. It is possible that these differences are partially explained by Grenada generally having lower background concentrations of $PM_{2.5}$. Another possibility is that PurpleAir monitors used in this study may have underestimated ambient dust concentrations. For example, it has been demonstrated in laboratory and ambient environments that Plantower sensor (contained in each PurpleAir monitor) $PM_{2.5}$ readings underestimated actual $PM_{2.5}$ concentrations when exposed to dusts.[264–266] One hypothesis by Kosmopoulos et al. (2020) states that high levels of coarse particles, such as during a NADD episode, lead to a different behavior of the PurpleAir monitor for the measurement of PM of varying sizes (PM_1, $PM_{1-2.5}$, $PM_{2.5}$, and PM_{10}).[265] It is also possible that laser channel-based sensor readings are affected by surface area, particle shape, colour and composition of dust particles.[264] In general, PurpleAir monitors have been shown to perform well in comparison to reference-grade monitors in previous studies.[240–242] However, few of these studies measured NADD events, and therefore, there would be value in pairing a higher grade monitor alongside a PurpleAir monitor to better understand possible exposure measurement error.

6.1.3. North African Desert Dust and Monthly Changes in Ambient $PM_{2.5}$

Monthly mean $PM_{2.5}$ concentrations in Grenada calculated in this study ranged from 2.92 to 8.06 μg/m^3. Aside from periods in which NADD episodes impacted Grenada air quality, most months had relatively low levels of ambient $PM_{2.5}$ measured. Months with the highest average monthly $PM_{2.5}$ concentrations measured, February (8.06 μg/m^3) and June (6.61 μg/m^3), appear to be driven by NADD episodes as there were 15 and 12 identified NADD days during these two months, respectively. Taken together, these findings suggest that NADD is the most important source of $PM_{2.5}$ exposure in Grenada.

A constructed annual cycle of dust mass concentration in Barbados based off historical observations (1973-2017) appears to be the closest available data to help contextualize measures of monthly mean $PM_{2.5}$ in Grenada.[267] The annual cycle of dust mass concentrations in Barbados shows that there is a clear season of maximum NADD transport to the southern Caribbean region, from May to September. The month with the highest monthly mean dust mass concentration in Barbados is June. This parallels June having the second highest monthly mean $PM_{2.5}$ concentration measured in Grenada, largely driven by frequent NADD episodes. However, February had the highest monthly mean $PM_{2.5}$ concentration in Grenada, here attributed to NADD episodes as well. At first glance this appears to be an anomaly that does not align with the annual cycle of dust transport to Barbados. Though, interestingly, the past decade in Barbados has been characterized by greater year-to-year variability in dust concentrations measured during spring (March to May) and summer (June to August) seasons than in years past.[267] Thus, the February 2020 peaks in daily mean $PM_{2.5}$ measured in this study in Grenada may be part of a trend of greater year-to-year variability in northern Africa dust mass emission and transport.

6.1.4. Day of Week Changes in Ambient $PM_{2.5}$

Daily median $PM_{2.5}$ concentrations on a day-of-week basis exhibited little variation, ranging from 3.12 to 4.23 μg/m^3. Thursday and Friday had the highest daily median $PM_{2.5}$ concentrations at 4.23 and 4.16 μg/m^3, respectively. In contrast, Monday and Tuesday had the lowest daily median $PM_{2.5}$ concentrations at 3.12 and 3.13 μg/m^3, respectively. It is possible that these trends are explained by human activities in Grenada taking a sharp decrease on Saturday and Sunday which allows for diffusion and absorption of particulate matter, leaving Monday and Tuesday with minimal formation of secondary aerosols. Then as the week goes on, secondary aerosols may accumulate with more human activity that peaks on Thursday and Friday with primary and secondary particulate emissions. A similar pattern in day-of-week ambient $PM_{2.5}$ was observed across the US.[268]

6.1.5. Differences in $PM_{2.5}$ by Location and Time of Day

This study found that differences in ambient $PM_{2.5}$ at urban and rural locations in Grenada varied by time of day. On a day-to-day basis, differences in $PM_{2.5}$ at urban and rural locations were modest as they tended not to vary by more than 1-2 μg/m^3 throughout the study period. On a time-of-day basis, $PM_{2.5}$ concentrations measured at the urban site monitor were higher than measures from the rural site monitor across the day. The time period of 3 PM to 9:59 PM in particular measured the greatest difference between urban and rural $PM_{2.5}$. This trend of higher $PM_{2.5}$ at the urban site from 3 PM to 9:59 PM may be due to increased vehicular traffic with the urban monitor being located near the only road on Grenada that allows medium to large trucks to traverse from major ports to northern parts of the island. It is likely not due to any diurnal meteorological changes because this large peak in $PM_{2.5}$ from 3 PM to 9:59 PM at the urban monitor was not found with the rural monitor.

Studies examining ambient $PM_{2.5}$ by time of day appear to have found similar results to those in this study. In Trinidad, concentrations of hourly $PM_{2.5}$ were lower early on in the day (1 AM to 4 PM) and peaked from 5 PM to 12 AM.[269] Researchers stated that hourly $PM_{2.5}$ trends were not influenced by rush-hour traffic, but rather due to transboundary pollution. In the Canary Islands, hourly $PM_{2.5}$ concentrations peaked between 12 to 5 AM due to seaward transport of particulates towards the shore (close to monitor locations), and the lowest values were measured during daylight (11 AM to 5 PM) due to the import of clean marine air inland.[270] While transboundary pollution and diurnal cycles in air mass flow are plausible explanations for the observed trends in time-of-day $PM_{2.5}$, these trends were not observed with the rural site monitors in Grenada. Thus, these trends in time-of-day $PM_{2.5}$ measured at the urban site monitor are likely due to motor vehicle traffic.

6.1.6. Daily Mean $PM_{2.5}$ and Daily Meteorological Measures

Of all the meteorological measures, daily mean visibility displayed the strongest (inverse) association with daily mean $PM_{2.5}$ ($r = -0.63$; $p<0.05$). In addition, visibility acted as a major determinant of NADD days in Grenada. Other than days with heavy fog, reductions in atmospheric visibility are heavily associated with poor air quality.[271] Generally, reductions in visibility are accompanied by the presence of ambient fine particulate matter due to its light-scattering and light absorption capabilities.[272] Inverse associations between daily measures of visibility and particulate matter pollution have been reported in many other regions.[273–276]

In addition to visibility, wind speed was modestly positively associated ($r = 0.26$; $p<0.05$) with $PM_{2.5}$. In Trinidad and Tobago, Shairsingh et al. (2020) reported a similar finding, as wind speed was associated (Spearman's correlation coefficient = 0.2; $p<0.001$) with hourly $PM_{2.5}$ concentrations.[269] However, this association was based on data collected over a 3-day interval. The authors hypothesized that the positive association between $PM_{2.5}$ and wind speed may be due to increased transboundary (e.g., NADD) pollution with increased wind speed conditions. This appears plausible as the wind direction in Grenada is eastwards for most of the year, the same direction of NADD transport to the Caribbean.[277] As well, dust storms are typically associated with higher wind speeds.[278] Here, this study in Grenada found wind speeds to be higher on NADD days (daily mean = 6.74 m/s) compared to non-NADD days (daily mean = 5.54 m/s). Thus, the occurrence of NADD episodes in Grenada appears to contribute to the modestly positive association observed between daily mean wind speed and $PM_{2.5}$.

Daily mean atmospheric pressure was also weakly associated with daily mean $PM_{2.5}$ ($r = 0.22$; $p<0.05$). In general, low pressure weather systems bring wet and windy conditions that wash out pollutants from the local air and transport them to a new area. In contrast, high pressure weather systems create stagnant air conditions that allow for emitted pollution to concentrate in a local area (i.e., higher ambient PM concentrations).[279,280] Thus, this finding appears to follow the usual relationship between these two variables.

Results also showed daily mean precipitation was not associated ($r = -0.03$; $p = 0.63$) with daily mean $PM_{2.5}$. Usually, a negative association between these two variables is plausible, as rainfall tends to wash out atmospheric pollutants from the air via wet deposition.[281–283] While on different temporal scales, Akpinar-Elci et al. (2015) found a weak association between monthly rainfall and recorded dust measurements ($R^2 = 0.07$; $p<0.001$) in one of the two previous studies on desert dust and human health in Grenada. Relative humidity usually has a similar effect as rainfall on ambient particulate matter, often resulting in particulate deposition (i.e., decrease in PM concentration) from increases in particulate size in high humidity conditions.[31–33] Here, this study found a very weak negative association ($r = -0.09$; $p = 0.13$) between daily mean relative humidity and daily mean $PM_{2.5}$.

Daily mean temperature was not associated with daily mean $PM_{2.5}$ ($r = -0.02$; $p = 0.70$). This finding appears to be an outlier when compared to a previous finding in the Caribbean. In Guadeloupe, Plocoste et al. (2020) documented the annual cycle of monthly mean PM_{10} concentrations and air temperature based off 11 years of data (taken from years 2005 to 2017).[284] They found that the annual cycle of PM_{10} and temperature followed the same pattern, exhibiting highest monthly mean values between May and September. This is nearly identical to the annual cycle of dust mass concentration in Barbados.[267] This study's finding of a very weak correlation between daily mean $PM_{2.5}$ and temperature is likely due to the atypical trends in ambient $PM_{2.5}$ and NADD (peaks in February, relatively low levels in May and August) in Grenada during the study period. Indeed, when correlations were calculated following the exclusion of values in February, the correlation between daily mean temperature and daily mean $PM_{2.5}$ became stronger, from -0.02 to 0.16 ($p<0.01$).

6.2. Impact of COVID-19 on Ambient $PM_{2.5}$ Concentrations

6.2.1. Public Health Measures and Ambient $PM_{2.5}$

The beginning of the pandemic in Grenada was characterized by the implementation of various public health measures (e.g., curfews, social gathering limits, air and boat travel restrictions, etc.) via the Emergency Powers Act. This study found the general presence of COVID-19 related public health measures in Grenada was associated with lower daily mean $PM_{2.5}$ concentrations. In a constructed multiple regression model, when adjusting for the occurrence of NADD days, daily mean wind speed, and daily mean atmospheric pressure, the general implementation of public health measures in Grenada was associated with a 0.52 $\mu g/m^3$ decrease in daily mean $PM_{2.5}$. Though, this multiple regression model explains the daily mean $PM_{2.5}$ concentrations averaged across all five installed monitors in this study. In a constructed multiple regression model to best explain daily mean $PM_{2.5}$ concentrations averaged across the four monitors installed on Grenada, while adjusting for the same covariates as the previous model, the general implementation of public health measures in Grenada was associated with a 0.51 $\mu g/m^3$ decrease in daily mean $PM_{2.5}$.

The two constructed multiple regression models had predicted similar levels of variance in daily mean $PM_{2.5}$ (0.40 and 0.37). A likely source of variation in daily mean $PM_{2.5}$ unaccounted for in either of the constructed multiple regression models is low-level concentrations of NADD. On any given day, Grenada can be the recipients of NADD transported in low amounts. This would be unaccounted for on days that were not explicitly identified as a 'NADD day' in this study. Another potential source of variation in daily mean $PM_{2.5}$ that was unaccounted for is sea-salt aerosols or biomass burning smoke. These are two sources of particulate matter that were not tracked throughout the study period. If particulate matter samples and compositional analyses were able to be performed throughout the study period, it would have helped determine the contribution of different sources of ambient particulate matter in Grenada.

The small decrease in daily mean $PM_{2.5}$ associated with public health measures is plausible for two main reasons. First, this association was found while adjusting for meteorological variables (NADD days, daily mean atmospheric pressure, and daily mean wind speed) that can potentially have an impact on ambient fine particulate matter. Demonstrating the importance of meteorological parameters, locations such as Beijing (China) and Tehran (Iran) have noticed increases in ambient $PM_{2.5}$ throughout lockdown periods that are likely due to reduced precipitation and wind speed, lower planetary boundary layer height, and the occurrence of dust storms.[193,194] Additionally, Grenada's climate consists of little variation in temperature and relative humidity which means they are likely not important factors in these observed changes in ambient $PM_{2.5}$. Secondly, implemented public health measures (most being lockdowns in the literature) across many countries have been associated with decreases in ambient $PM_{2.5}$.[12] Thus, the findings for Grenada are consistent with other published data.

6.2.2. Specific Public Health Measures and Ambient $PM_{2.5}$

Curfews were a major part of the initial public health measures in Grenada. Interestingly, this study did not find a meaningful association between the implementation of curfews and daily mean $PM_{2.5}$. A study examining the impact of COVID-19 related lockdown measures on air quality across 162 countries found that the isolated implementation of curfews alone resulted in decreased $PM_{2.5}$, though the decrease was only noticeable after a month delay.[285] However, the implementation of a state of emergency **and** curfews resulted in decreased $PM_{2.5}$ almost immediately. Curfews in Grenada were accompanied by a state of emergency and yet no meaningful association was found between curfews and daily mean $PM_{2.5}$, which appears to run contrary to the literature.

Social gathering limits were another part of the implemented public health measures by Grenada's government to reduce social interaction during the pandemic. Analyses performed here did not find a meaningful association between social gathering limits (excluding wedding and funeral social gathering limits) and daily mean $PM_{2.5}$. While there are many studies that examine lockdown measures (which often include social gathering limits) and ambient air quality changes, none could be identified that specifically examined the implementation of social gathering limits and changes in ambient air quality.

With Grenada's implementation of commercial air travel restrictions in March 2020, it was of interest to investigate its potential impact on ambient fine particulate matter levels around the island. However, throughout the study period, no meaningful association was found between daily (commercial) airplane movements and daily mean $PM_{2.5}$. While 4 monitors were intermittently collecting ambient $PM_{2.5}$ measurements throughout most of the period (March 23 to July 15, 2020) with the most stringent air-travel restrictions in Grenada, the airport located monitor was only installed on August 24, 2020. Thus, some of the local impacts on ambient $PM_{2.5}$ in the airport area with the implementation of air-travel restrictions may have been missed. Capturing the local impacts of changes in airplane traffic is important because it is generally the dominant source of ambient air pollution at airports.[286] However, no studies could be identified presently that also examined impacts of changes in commercial airplane flights due to COVID-19 and surrounding ambient air quality.

Due to Grenada's restrictions on boat/ship travel, the relationship between daily boat/ship movements and daily mean $PM_{2.5}$ was also investigated. However, a statistically significant association between the two variables could not be detected during the study period. A potential reason why the true relationship between these two variables may not have been captured is that there were not many recorded high-volume days (10+) of boat/ship movements to compare against days of lower movement volume. As well, no monitors were installed close to any of Grenada's main ports, thereby missing a potential localized impact of the changes in boating/shipping traffic. This would be worth examining in future studies. While there were studies identified that demonstrate reductions in boating/shipping traffic and emissions during COVID-19,[287,288] no studies could be identified that examined changes in boating/shipping traffic activity or boat/ship movements with ambient air pollution during the pandemic.

6.2.3. Ambient $PM_{2.5}$ in 2020 vs 2021

Due to the lack of historical ambient air pollution data recorded in Grenada, the best method available to help contextualize daily ambient $PM_{2.5}$ values throughout 2020 is by comparing them to values measured in 2021. Thus, a time-series was constructed using 3-day rolling mean $PM_{2.5}$ measured at the Tempe monitor, comparing data from January 1 to April 6 in 2020 and 2021.

As described earlier, COVID-19 restrictions first began in Grenada on March 16, 2020, with a cruise ship advisory that prohibited passengers from disembarking.[211] This was followed by more restrictions on boating/shipping activities, and commercial airplane flights on March 20 and 23, respectively.[212,213] On March 25, wide-sweeping COVID-19 restrictions were first implemented via the "Emergency Powers (COVID-19) Regulations, 2020" which implored mandatory curfews, business closures, limited social gathering and restrictions on non-essential use of vehicles and public transportation.[214] These restrictions extended past April 6, 2020.[215]

In 2021, Grenada had varying levels of COVID-19 restrictions from January 1 until April 6. From the beginning of January, Grenada had curfews implemented from 8 PM to 5 AM which gradually became more relaxed as time passed.[289] By April 6, daily curfews were reduced to 12 AM to 4 AM.[290] From January 1 to January 11, social gatherings were limited to 10 people for private gatherings, weddings, and funerals.[289,291] From January 11 to April 6, social gatherings were limited to 20 people for private gatherings, weddings, and funerals.[290,292,293] Throughout the January to April period in 2021, businesses were required to close at an earlier time than normal. From January 1 to January 10, all non-essential businesses were required to close by 8 PM,[289] and from January 11 to April 6, all non-essential businesses had to close by 10 PM.[292] Also during this January to April 2021 time period, Grenada permitted regional flights to and from neighbouring Caribbean nations (e.g., Antigua, Barbados, St. Vincent and the Grenadines) as well as international flights to and from countries such as Canada and the USA.[294]

The trends in 3-day rolling mean $PM_{2.5}$ appear to be similar between January 1 and April 6 in 2020 and 2021. In particular, daily mean $PM_{2.5}$ values from February to March were quite similar, considering the lack of COVID-19 restrictions during this time period in 2020, contrasted by the presence of COVID-19 restrictions during this time period in 2021. However, this comparison is not exhaustive and further data collection is required to better contextualize measured $PM_{2.5}$ values during periods of COVID-19 restrictions being implemented in Grenada.

6.3. Limitations

In addition to the potential underestimation of dusts by the PurpleAir monitors, discussed in the *North African Desert Dust and Daily Changes in Ambient $PM_{2.5}$* subsection, there are three other aspects of this thesis project that were responsible for the most significant limitations for this work. These three aspects of the project include: the impact of high humidity on the PurpleAir PA-II-SD monitors, the lack of historical data previously recorded in Grenada, and the measurement of ambient fine particulate matter to quantify local changes in ambient air pollution during COVID-19.

Over the course of the study period, several of the PurpleAir PA-II-SD monitors broke down and required repair. These monitor breakdowns are suspected to be because of a combination of high humidity and sea-salt spray exposure. In Grenada, relative humidity levels were routinely above 70%. As well, four monitors (Egmont, Bathway, Windward, and Airport) were close to a coastline, indicating the potential for consistent exposure to sea-salt spray. It is possible the combined high humidity and sea-salt spray may have impacted internal parts of monitors that broke down, such as corroding the power cord or impacting the laser channels that are responsible for particle measurements.

The second major limitation of this project is due to the lack of historical data to compare our $PM_{2.5}$ measurements against. A lack of historical data means there is a lack of knowledge of the year-to-year variability in $PM_{2.5}$ concentrations in Grenada. This makes it difficult to put measured $PM_{2.5}$ concentrations during this study period in context with normal conditions in Grenada, especially throughout the COVID-19 pandemic. Thus, it is uncertain if the decrease in daily mean $PM_{2.5}$ during the period of public health interventions was due to decreased anthropogenic activities, or just part of the annual cycle in ambient $PM_{2.5}$ in Grenada. In Figure 10, daily mean $PM_{2.5}$ concentrations measured in Grenada in 2020 and 2021 appear to be relatively similar. However, this comparison of 2020 and 2021 ambient $PM_{2.5}$ in Grenada is by no means exhaustive. Thus, it supports the need for more long-term collection of ambient air pollutant concentrations on the island.

The final major limitation of this project is that measurements of ambient fine particulate matter to quantify impacts of pollution changes during COVID-19 is sufficient, but it may not be optimal. Particles are able to travel further than gaseous pollutants, therefore, measures of fine particulate matter will include both local and regional sources of pollution. In contrast, measurements of ambient NO_2 may have been more helpful in achieving the second objective of this project. Ambient NO_2 is a good indicator of traffic pollution,[20] thus measuring it could have helped better quantify the impacts of curfews and social gathering limits on ambient air quality. As well, installing a PurpleAir monitor closer to a major port in Grenada likely would have better captured any local changes in ambient air quality throughout COVID-19.

6.4. Strengths

Among the most significant strengths of this project is the collection of ambient $PM_{2.5}$ data in Grenada for nearly 10 months that allowed for the characterization of day-to-day variations, time-of-day variations, and to assess the impacts of NADD days. Day-to-day variations in ambient particulate matter have been performed in Guadeloupe,[177,284] but never before in Grenada. Trinidad and Tobago are the only other Caribbean islands that have had hourly measures of ambient air pollutants reported in a study.[269] However, these hourly measures were from a small sample size (~3 days), which is not as exhaustive as the hourly $PM_{2.5}$ measurements taken over 10 months for this project in Grenada. Additionally, Guadeloupe appears to be the only other Caribbean island that has had the impacts of NADD days on day-to-day ambient $PM_{2.5}$ concentrations examined.[177] Altogether, this study provides initial ambient $PM_{2.5}$ exposure data to justify future studies in Grenada.

Another strength of this study was demonstrating that most days of high (~15 to 20 $\mu g/m^3$) ambient $PM_{2.5}$ were due to NADD episodes. This yields an important finding, that natural sources of ambient air pollution appear to be impacting outdoor air quality in Grenada much more than local anthropogenic sources. In addition, this study adds to the historical record of dust transport to this southern Caribbean region. This is important because in the last decade, it appears as though seasonal patterns (particularly spring and summer) of dust transport to the Caribbean have been more erratic,[267] potentially due to anthropogenic induced climate change.[295] Observations of NADD episode occurrence in Grenada in 2020 appear to be in-line with this change in dust transport trends to the Caribbean in the last decade.

This study also improved upon existing methods of identifying NADD days in the Caribbean region, that is, when collecting physical samples of dust particles is not an option. The method used in this study can be replicated with relative ease, so long as daily visibility measures can be obtained, and internet access is available to utilize online tools such as the Naval Research Laboratory's NAAPS Global Aerosol Model and MERRA-2 derived dust aerosol optical thickness maps.

A final strength of this project is that it is among the first to quantify the impacts of COVID-19 related public health measures on ambient air quality in the Caribbean region. Measures of ambient $PM_{2.5}$ in Grenada throughout COVID-19 suggests that human activities are not driving major changes in ambient air pollution on the island. Though, further collection of ambient $PM_{2.5}$ in Grenada is required to confirm this hypothesis. As well, this project is among the first to examine the impacts of specific COVID-19 related public health measures and ambient $PM_{2.5}$.

6.5. Recommendations

In future work, a monitoring network such as the one constructed in this study could benefit from an accompanying reference grade monitor side-by-side one of the low-cost sensors to compare measures of ambient $PM_{2.5}$. Reference grade monitors that have drying or heating facilities would be beneficial to use because they can mitigate the impacts of high relative humidity conditions by removing all liquids from the particles that are being measured.[296] This is important because the presence of water on the particles plays no part in the adverse health effects particulate matter causes upon exposure.

To better understand the long-term trends in air pollution and impacts on health in Grenada, continued long-term monitoring of air pollution is recommended. This is for two main reasons. First, continued monitoring of ambient $PM_{2.5}$ would aid in recording future impacts of NADD episodes in the Caribbean. This would help determine if the erratic seasonal trends in dust transport to the Caribbean of the previous decade[267] continues into the future. Secondly, continued monitoring of ambient $PM_{2.5}$ would help contextualize the trends in ambient $PM_{2.5}$ throughout COVID-19. It is important to know if the slightly lower daily mean $PM_{2.5}$ concentrations found here with the general implementation of public health measures is due to seasonal changes in ambient particulate matter in Grenada, or due to changes in human activity during COVID-19.

It may also be a good idea to use NO_2 monitors in future studies in Grenada to better capture local impacts of traffic emissions. This is because particles are able to travel further than gaseous pollutants. Therefore, measures of fine particulate matter will include both local and regional sources of pollution. In contrast, measuring ambient NO_2 is a good indicator of traffic emissions[20] and likely won't be as impacted by regional sources of pollution.

A final recommendation would be to explore creating an LUR model for the St. George's area, Grenada's capital city. LUR models can be particularly advantageous for characterizing pollutant concentration variability on small spatial scales. For St. George's, installing 20-30 high-grade monitors for two-week periods throughout multiple seasons of a given year should satisfy the data requirements for constructing such an LUR surface. This LUR could be constructed from ambient measurements of NO_2, $PM_{2.5}$, or $PM_{0.1}$.

6.6. Conclusion

In conclusion, collected ambient $PM_{2.5}$ measurements in Grenada suggest that the ambient concentrations of this pollutant are lower than most other countries. Nonetheless, the impacts of NADD episodes are severe and responsible for nearly all days of high ambient air pollution on the island. This work also suggests that public health restrictions during COVID-19 modestly reduced concentrations of $PM_{2.5}$. Future work should explore locally based sources of exposure that were not able to be assessed using our limited network of monitors, and evaluate the extent to which increases in $PM_{2.5}$ may increase the risk of adverse health events.

7. Appendices

Appendix A. Summary of Desert Dust and Human Health Studies

***Table A7**: Summary of desert dust and human health studies*

Author	**Place of Study**	**Population**	**Study Design**	**Pollutant Examined**	**Outcome**	**Health Impacts**		
				Morbidity				
Akpinar-Elci M, et al. (2015)[8]	Grenada, West Indies	All ages	Retrospective ecological study	Saharan Dust concentration	Emergency Department Visits for Asthma	Weak positive association between mean monthly asthma visits and dust concentration from 2001-2005 (R^2 = 0.04 $p < 0.001$)		
Cadelis G, Tourres R, and Molinie J (2014)[177]	Guadeloupe, French West Indies	Ages 5 to 15	Time-stratified case-crossover study	PM_{10}	Emergency Department Visits for Asthma	**IR%[9] per 10 ug/m^3 increase in PM_{10}** +9.1% (DD)[10]	**(95% CI)[12]** (7.1-11.1%)	**[Days before dust event]** [lag 0][13]

[9] Excess risk percentage (IR%)
[10] Dust Day (DD)
[12] 95% confidence interval (95% CI)
[13] Effects of exposure examined the same day (lag 0)

						+1.1% (NDD)[11] +5.1% (DD) +2.4% (NDD)	(-5.9-4.6%) (1.8-7.7%) (-0.3-5%)	[lag 0]*[14] [lag 0-1][15] [lag 0-1]*
				$PM_{2.5-10}$		+4.5 % (DD) +1.6% (NDD) +4.7 % (DD) +1.8% (NDD)	(3.3-5.7%) (-6.5-10.4%) (2.5-6.5%) (-1.1-3.4%)	[lag 0] [lag 0]* [lag 0-1] [lag 0-1]*
				$PM_{2.5}$		+1.4% (DD) +1.1% (NDD) +1.4% (DD) +1.3% (NDD)	(-0.6-5.2%) (-4.5-7.7%) (-2.7-5.0%) (-4.1-6.5%)	[lag 0]* [lag 0]* [lag 0-1]* [lag 0-1]*
Gyan K, et al. (2005)[175]	Trinidad, West Indies	Ages 15 and under	Retrospective ecological study	Saharan Dust (Visibility used to identify	Accident and Emergency Department	A deterioration in visibility from no dust (visibility = 7 km) to very dusty (visibility = 16 km) estimated to increase daily admission rate for paediatric asthma, from 7.8 to 9.25. Lagged		

[11] Non-Dust Day (NDD)
[14] Non-statistically significant results (*)
[15] Effects of exposure examined one day before until day of event (lag 0-1)

				desert dust events)	Visits for Asthma	effects of two or more days after dust cover had no impact on number of daily asthma visits.	
Ortiz-Martinez MG, et al. (2015)[179]	Puerto Rico, West Indies	Ages 0 to 18	Retrospective ecological study	PM_{10} (during dust day)	Pediatric Hospital Services Offered to Asthma Cases	Asthma cases during Saharan dust event associated to Rural Site PM_{10} ($R = 0.55$, $p = 0.04$) and not significantly associated to Urban Site PM_{10} ($R = 0.47$, $p = 0.09$)* in 2004	
Prospero J, et al. (2008)[176]	Barbados, West Indies	Ages 0 to 18	Time-series study	Saharan Dust concentration	Daily Pediatric Asthma Hospital Visits	No obvious relationship found between dust surges and daily pediatric asthma visits	
Samoli E, et al. (2011)[297]	Athens, Greece	Ages 0 to 14	Time-series study	PM_{10}	Emergency Department Visits for Asthma	**% Change in Visits per 10 ug/m^3 increase in PM_{10}** +4.1 % (DD) +2.1% (NDD)	**(95% CI)** (0.1-8.3%) (-1.0-5.2%)
Trianti SM, et al. (2017)[298]	Athens, Greece	Ages 18 and over	Case-crossover study	Desert Dust Days (adjusting for PM_{10})	Emergency Asthma Visits	**% Change in Visits per 10 ug/m^3 increase in PM_{10}** +36.33%	**(95% CI)** (14.79-61.91%)

						(relative to non-desert dust days)		
					Emergency COPD Admissions	+52.91% (relative to non-desert dust days)		(29.35-80.75%)
					Emergency Respiratory Infections Admissions	+60.49% (relative to non-desert dust days)		(35.02-90.77%)
					Emergency Respiratory Admissions	+45.25% (relative to non-desert dust days)		(26.75-66.45%)
Chang CC, et al. (2006)[299]	Taipei, Taiwan	All ages	Case-crossover study	Asian Dust Events	Allergic Rhinitis Clinic Visits	**RR**[16] 1.09 1.11 1.19 1.08	**(95% CI)** (0.89-9.43) (0.92-9.68) (0.98-11.39) (0.89-9.17)	**[Days after dust event]** [lag 0]* [lag 1]* [lag 2]* [lag 3]*

[16] Relative Risk (RR)

Cheng MF, et al. (2008)[300]	Taipei, Taiwan	All ages	Case-crossover study	Asian Dust Events	Pneumonia Clinic Visits	**RR** 1.03 1.05 1.04 1.04	**(95% CI)** (0.98-1.09) (1.00-1.10) (1.00-1.09) (0.99-1.08)	**[Days after dust event]** [lag 0]* [lag 1] [lag 2]* [lag 3]*
Gutierrez MP, et al. (2020)[301]	Miami, USA	Miami Veterans with COPD	Prospective cohort study	Saharan Dust Event Occurrence	Acute Exacerbation of COPD (AECOPD)	**OR[17] for 2+ AECOPD among Miami Veterans** 19.93 15.16 14.44 16.06 7.02 7.48	**(95% CI)** (2.62-151.55) (1.90-121.29) (1.92-108.59) (2.15-119.79) (1.61-30.60) (1.73-32.40) (1.84-34.35) (1.54-103.35)	**[Days after dust exposure]** [lag 1] [lag 2] [lag 4] [lag 5] [lag 7] [lag 8] [lag 9]

[17] Odds Ratio (OR)

						7.96	(1.56-95.29)	[lag 10]
						12.62	(1.39-27.19)	[lag 11]
						12.19	(1.51-29.21)	[lag 12]
						6.15	(1.32-78.44)	[lag 13]
						6.64		[lag 14]
						10.17		
Vodonos A, et al. (2014)[302]	Be'er Sheva, Israel	Ages 18 and older	Time-series study	PM_{10} (during mild dust storm days)	Hospital visits for COPD exacerbation	**IRR[18] per IQR increase in PM_{10}** 1.12 (relative to non-dust days)	**(95% CI)** (1.03-1.21)	**[Days after dust exposure]** [lag 0]
				PM_{10} (during intensive dust storm days)		1.27 (relative to non-dust days)	(1.12-1.43)	[lag 0]

[18] Incidence Relative Risk (IRR)

Tam WWS, et al. (2012)[303]	Hong Kong	All ages	Case-crossover study	$PM_{2.5-10}$ (during Asian Dust Event)	Emergency Hospital Admissions for all CVD	**RR per 10 μg/m^3 increase in $PM_{2.5-10}$** 1.01 1.02 1.01	**(95% CI)** (0.98-1.04) (1.00-1.05) (0.98-1.05)	**[Days after dust exposure]** [lag 0] [lag 1] [lag 2]
					Emergency Hospital Admissions for IHD	1.04 1.04 1.05	(1.00-1.08) (0.99-1.09) (0.98-1.13)	[lag 0] [lag 1] [lag 2]
Chan CC, et al. (2008)[304]	Taipei, Taiwan	All ages	Time-series study	High Dust Event (PM_{10} greater than 90 μg/m^3)	Emergency Visits for CVD	**Difference in CVD Visits** +1.5 CVD visits/dust event (relative to pre-dust periods)	**(95% CI)** (0.3-2.6)	
				Low Dust Event (PM_{10}		+0.2 CVD visits/dust event (relative to pre-dust periods)	(-0.9-1.2)	

				less than 90 μg/m^3)				
Reyes M, et al. (2014)[305]	Madrid, Spain	All ages	Ecological time-series study	PM_{10} (during Saharan dust days)	Respiratory Hospital Admissions	**RR per 10 μg/m^3 increase** 1.02 1.03	**(95% CI)** (1.00-1.04) (1.00-1.06)	**[Days after dust exposure]** [lag 1] [lag 7]
				$PM_{2.5-10}$ (during Saharan dust days)		1.08	(1.03-1.14)	[lag 5]
Middleton N, et al. (2008)[306]	Nicosia, Cyprus	All ages	Time-series study	Desert Dust Days	Cardiovascular Hospital Admissions	**% Change in Admissions** +10.4%* (relative to non-dust days)		**(95% CI)** (-4.7-27.9%)
					Respiratory Hospital Admissions	+3.1%* (relative to non-dust days)		(-10.2-18.3%)

Yang CY, et al. (2005)[307]	Taipei, Taiwan	All ages	Case-crossover study	Asian Dust Events	Daily primary intracerebral hemorrhagic stroke admissions	**RR** 0.96* 1.01* 0.99* 1.15	**(95% CI)** (0.82-7.03) (0.88-7.84) (0.95-7.81) (1.01-10.10)	**[Days after dust exposure]** [lag 0] [lag 1] [lag 2] [lag 3]
Yang CY, et al. (2009)[308]	Taipei, Taiwan	All ages	Case-crossover study	Asian Dust Events	Hospital admissions for CHF	**RR** 0.92* 1.11* 0.98* 0.97*	**(95% CI)** (0.81-1.04) (0.99-1.25) (0.87-1.11) (0.87-1.09)	**[Days after dust exposure]** [lag 0] [lag 1] [lag 2] [lag 3]
Mortality								
Neophytou AM, et al. (2013)[309]	Nicosia, Cyprus	All ages	Time-series study	PM_{10}	Daily Cardiovascular Mortality	**% Change in Daily Mortality per 10 $\mu g/m^3$ increase** +2.43% (DD) +0.19% (NDD)	**(95% CI)** (0.53-4.37%) (-2.12-2.53%)	

					Daily Respiratory Mortality	-0.79% (DD) -0.47% (NDD)	(-4.69-3.29%) (-4.39-3.61%)	
					Daily All-Cause Mortality	+0.13% (DD) -0.66% (NDD)	(-1.03-1.30%) (-1.88-0.58%)	
Tobías A, et al. (2011)[310]	Madrid, Spain	All ages	Case-crossover study	$PM_{2.5-10}$	Daily All-Cause Mortality	**% Change in Daily Mortality per 10 $\mu g/m^3$ increase** +2.8% (DD) +0.6% (NDD)	**(95% CI)** (0.1-5.8%) (-1.1-2.4%)	
Jiménez E, et al. (2010)[311]	Madrid, Spain	Ages over 75	Ecological longitudinal time-series study	PM_{10} (during Saharan dust days)	Daily Circulatory Mortality	**RR per 10 $\mu g/m^3$ increase** 1.04	**(95% CI)** (1.02-1.06)	**[Days after dust exposure]** [lag 3]
					Daily Respiratory Mortality	1.04	(1.01-1.06)	[lag 1]

Samoli E, et al. (2011)[312]	Athens, Greece	All ages	Case-crossover study	PM_{10} (during dust days and non-dust days)	Daily Total Mortality	The effect of a 10 μg/m^3 increase in PM_{10} on total mortality during non-dust days (+1.03%, 95% CI: 0.68-1.39%) was higher than during dust days (~0%, 95% CI NA)		
Sajani SZ, et al. (2010)[313]	Emilia-Romagna, Italy	Ages 75 and over	Case-crossover study	Saharan Dust Event Occurrence	Respiratory Mortality (Throughout Whole Year Model)	**OR** 1.22	**(95% CI)** (1.04-1.43)	
					Respiratory Mortality (During Hot Season Model)	1.34	(1.08-1.65)	
Díaz J, et al. (2012)[314]	Madrid, Spain	All ages	Case-crossover study	Saharan Dust Events	Daily Respiratory Mortality (Cold Season)	**IR% (Percentage increases in risk of death)**	**(95% CI)**	**[Days after dust exposure]**
						+3.34%	(0.36-6.41%)	
						(DD)*	(1.30-4.47%)	[lag 1]
								[lag 1]

						+2.87% (NDD)*		
					Daily Respiratory Mortality (Warm Season)	-0.05% (DD)* -0.59% (NDD)*	(-3.95-4.01%) (-4.22-3.17%)	[lag 1] [lag 1]
					Daily Circulatory Mortality (Cold Season)	-0.16% (DD)* +0.83% (NDD)*	(-2.41-2.14%) (-0.33-2.00%)	[lag 1] [lag 1]
					Daily Circulatory Mortality (Warm Season)	+4.19% (DD)* +2.65% (NDD)*	(1.34-7.13%) (0.12-5.23%)	[lag 1] [lag 1]
Perez L, et al. (2012)[315]	Barcelona, Spain	All ages	Time-stratified case-	$PM_{2.5\text{-}10}$	Cardiovascular Mortality	**OR per IQR increase** 1.09 (DD) 1.03 (NDD)	**(95% CI)** (1.02-1.16) (1.01-1.06)	**[Days before dust exposure]** [lag 1]

			crossover study					[lag 1]
Mallone S, et al. (2011)[316]	Rome, Italy	Ages 35 and over	Time-series study	$PM_{2.5-10}$	Cardiac Disease Mortality	**IR% per IQR increase** +9.73% (DD) +0.86% (NDD)	**(95% CI)** (4.25-15.49%) (-2.47-4.31%)	**[Days before dust exposure]** [lag 0-2] [lag 0-2]
					Circulatory Disease Mortality	+7.93% (DD) +2.21% (NDD)	(3.20-12.88%) (-0.74-5.25%)	[lag 0-2] [lag 0-2]
				PM_{10}	Cardiac Disease Mortality	+9.55% (DD) +2.09% (NDD)	(3.81-15.61%) (-0.76-5.02%)	[lag 0-2] [lag 0-2]
					Circulatory Disease Mortality	+5.91% (DD)* +1.82% (NDD)*	(1.02-11.03%) (-0.61-4.32%)	[lag 0-2] [lag 0-2]
Dominguez-Rodriguez	Tenerife, Canary	Patients with HF	Case-crossover study	Saharan Dust Event Exposure	Mortality in HF patients	**OR** 2.79	**(95% CI)** (1.066-7.332)	

A., et al. (2020)[317]	Islands, Spain			and > 50μg/m³				
Al-Taiar A and Thalib L (2013)[318]	Kuwait	All ages	Retrospective ecological time-series study	Desert Dust Events (with PM_{10} > 200 μg/m³)	Cardiovascular Mortality	**RR** 0.98* 0.99* 0.99* 0.99* 1.00*	**(95% CI)** (0.96-1.01) (0.96-1.02) (0.96-1.02) (0.96-1.02) (0.97-1.03)	**[Days after dust exposure]** [lag 0] [lag 1] [lag 2] [lag 3] [lag 5]
					Respiratory Mortality	0.96* 0.96* 1.00* 1.03* 1.01*	(0.88-1.04) (0.88-1.04) (0.92-1.08) (0.95-1.12) (0.93-1.09)	[lag 0] [lag 1] [lag 2] [lag 3] [lag 5]
					All-Cause Mortality	0.99* 0.99* 0.99* 1.00* 0.99*	(0.97-1.01) (0.97-1.01) (0.98-1.01) (0.96-1.04) (0.97-1.01)	[lag 0] [lag 1] [lag 2] [lag 3] [lag 5]

Appendix B. Comparison of $PM_{2.5}$ Daily Concentrations derived using Low-Cost PurpleAir Monitors (Grenada) versus a Reference-Grade Monitor (Martinique)

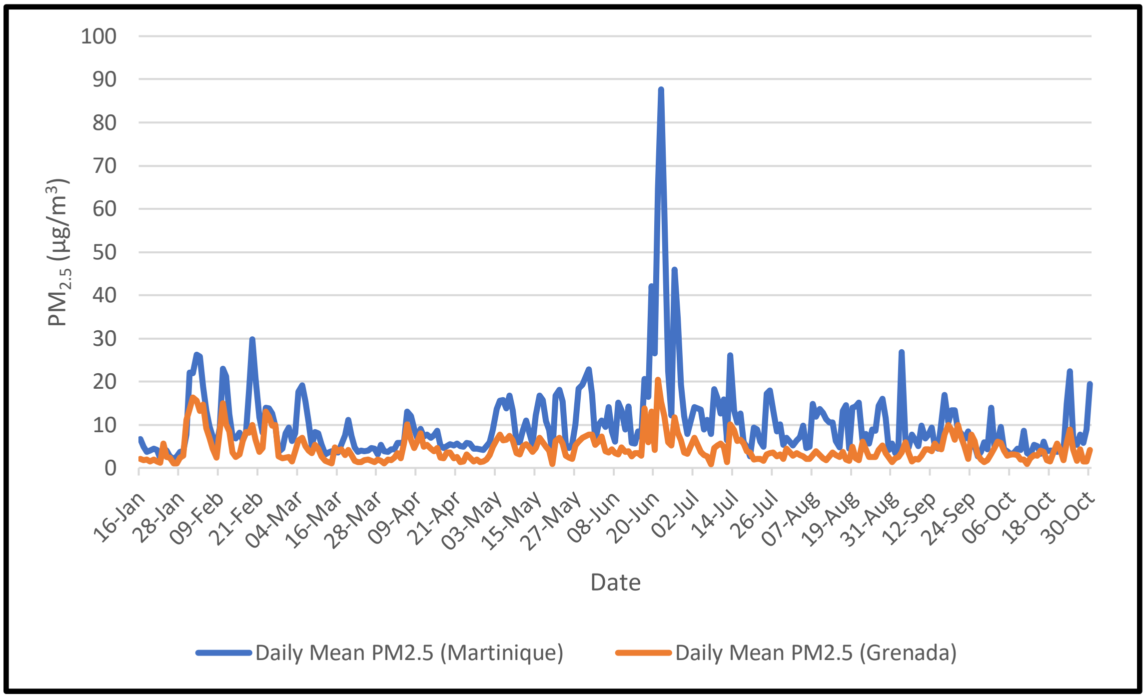

Figure 11*: A line graph comparison of daily mean $PM_{2.5}$ concentrations measured from five PurpleAir monitors on Grenada (orange) and one reference grade monitor on Martinique (blue). Measurements are compared from January 16 to October 30, 2020 (except May 30, July 1, 3, and 31 due to absence of data from the Martinique monitor).*

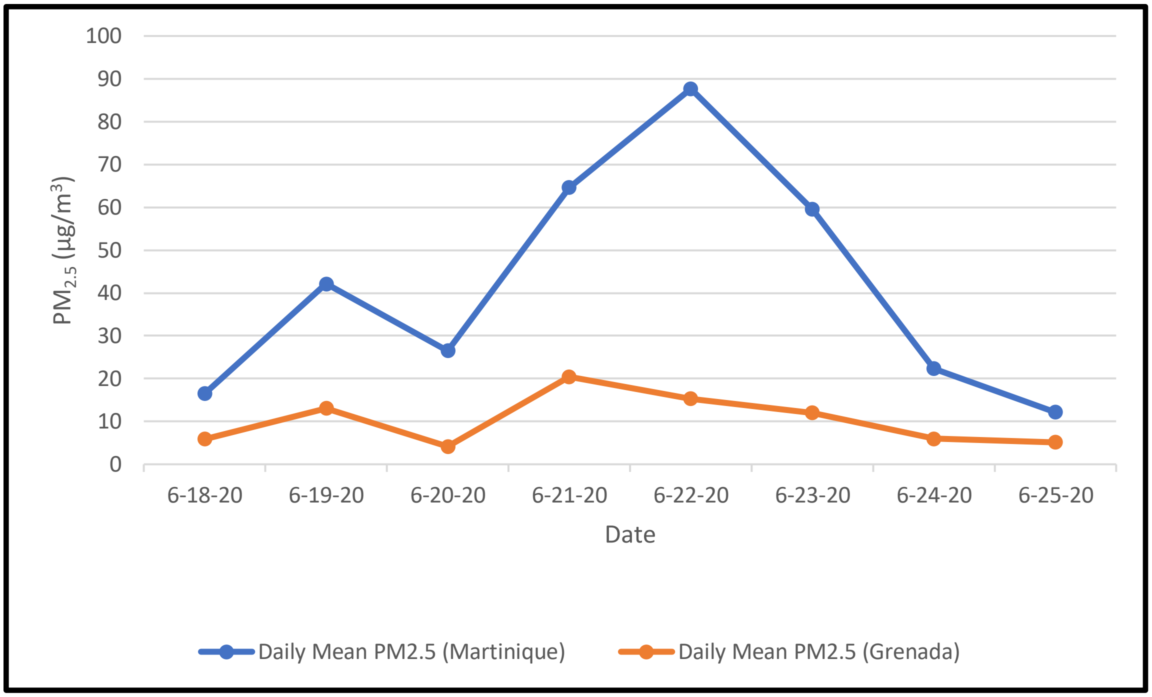

***Figure 12**: A line graph comparison of daily mean $PM_{2.5}$ concentrations measured during the June 2020 North African desert dust storm that impacted air quality throughout the Caribbean. Measured concentrations averaged from four PurpleAir monitors in Grenada and Carriacou (orange), and the reference grade monitor in Martinique (blue) are shown in this graph.*

Appendix C. Variations in the Concentrations of Ambient $PM_{2.5}$ by Month, Day of Week, and Presence of North African Desert Dust Days

Table C8: *Monthly mean $PM_{2.5}$ concentrations averaged from each of the five PurpleAir monitors installed in Grenada and Carriacou. These monthly mean PM2.5 concentrations account for all daily data measured from January 7 to October 31, 2020.*

	$PM_{2.5}$						
Month	Minimum	1st Quartile	Median	Mean	3rd Quartile	Maximum	SD
January	0.73	1.83	2.46	3.79	5.49	13.67	3.29
February	2.28	3.67	8.35	8.06	10.07	16.30	4.43
March	1.01	1.60	2.47	2.92	4.10	7.01	1.66
April	1.28	1.98	2.83	3.57	4.57	10.10	2.13
May	0.88	3.86	5.53	5.16	6.46	7.71	1.79
June	2.73	3.59	4.93	6.61	7.56	20.42	4.42
July	0.84	2.21	3.50	3.93	5.10	10.13	2.21
August	1.39	2.22	2.75	2.98	3.49	6.02	1.08
September	1.37	2.35	4.09	4.52	6.13	9.92	2.52
October	0.95	1.93	3.13	3.44	4.22	8.92	1.74

Table C9: *Day of week $PM_{2.5}$ concentrations averaged from each of the five PurpleAir monitors installed in Grenada and Carriacou. These day of week $PM_{2.5}$ concentrations account for all daily data measured from January 7 to October 31, 2020.*

	$PM_{2.5}$						
Weekday	Minimum	1st Quartile	Median	Mean	3rd Quartile	Maximum	SD
Monday	1.060	2.020	3.115	4.619	5.270	15.330	3.849577
Tuesday	0.730	2.070	3.130	4.189	5.150	14.660	3.075361
Wednesday	0.880	2.110	3.210	4.283	5.685	13.860	2.853676
Thursday	1.430	2.410	4.230	4.623	6.360	11.080	2.426707
Friday	1.280	2.925	4.160	4.797	5.880	13.670	2.877349
Saturday	1.010	2.490	3.430	4.095	4.885	16.300	2.593799
Sunday	0.950	2.373	3.590	4.795	5.848	20.420	3.963441

Table C10: *Summary measures of daily mean $PM_{2.5}$ concentrations during NADD days (Dust Day) and non-NADD days (Non-Dust Day).*

	$PM_{2.5}$						
Conditions	Minimum	1st Quartile	Median	Mean	3rd Quartile	Maximum	SD
Dust Day (48 days)	2.69	6.26	7.87	8.90	11.86	20.42	4.02
Non-Dust Day (257 days)	0.73	2.11	3.13	3.64	4.59	11.08	2.01

Appendix D. Variations in Meteorological Measures and Ambient $PM_{2.5}$ by Month

Table D11: *Monthly mean values of meteorological measures and ambient $PM_{2.5}$ in Grenada from January 6 to October 31, 2020.*

	Monthly Mean Meteorological Measures +/- Standard Deviation values						
Month	Atmospheric Pressure (mbs)	Precipitation (mm)	Relative Humidity (%)	Temperature (Celsius)	Visibility (km)	Wind Speed (m/s)	$PM_{2.5}$ ($\mu g/m^3$)
January	1014.37 +/- 1.19	0.85 +/- 1.24	77.82 +/- 3.59	26.83 +/- 3.59	21.19 +/- 3.50	5.04 +/- 1.55	3.79 +/- 3.29
February	1014.91 +/- 1.01	2.42 +/- 5.68	76.07 +/- 3.72	26.67 +/- 3.72	16.33 +/- 3.82	5.91 +/- 1.07	8.06 +/- 4.43
March	1014.40 +/- 1.43	0.65 +/- 1.46	74.38 +/- 4.84	26.69 +/- 4.84	22.02 +/- 2.73	5.18 +/- 2.00	2.92 +/- 1.66
April	1014.25 +/- 1.15	0.39 +/- 1.42	76.03 +/- 2.96	27.66 +/- 2.96	22.01 +/- 3.10	6.49 +/- 1.04	3.57 +/- 2.13
May	1014.51 +/- 0.83	0.20 +/- 0.91	76.08 +/- 2.39	28.48 +/- 2.39	18.02 +/- 2.58	7.34 +/- 0.79	5.16 +/- 1.79
June	1013.78 +/- 1.14	4.40 +/- 9.45	79.35 +/- 5.86	27.88 +/- 5.86	15.47 +/- 4.40	6.43 +/- 1.44	6.61 +/- 4.42
July	1012.88 +/- 0.85	1.82 +/- 3.79	78.89 +/- 3.95	28.49 +/- 3.95	18.20 +/- 2.90	6.32 +/- 1.59	3.93 +/- 2.21

August	1012.38 +/- 1.68	4.65 +/- 7.99	81.31 +/- 4.09	28.57 +/- 4.09	19.57 +/- 2.88	5.09 +/- 1.58	2.98 +/- 1.08
September	1011.52 +/- 1.28	1.83 +/- 3.75	79.67 +/- 2.76	28.77 +/- 2.76	21.91 +/- 3.71	4.06 +/- 1.49	4.52 +/- 2.52
October	1011.51 +/- 1.26	4.96 +/- 8.08	80.52 +/- 2.76	28.37 +/- 2.76	20.04 +/- 3.91	5.48 +/- 1.86	3.44 +/- 1.74

Appendix E. Descriptive Statistics and Simple Regression Results

Table E12: *Descriptive statistics and simple regression results from comparing each characteristic variable with daily $PM_{2.5}$ averaged from each of the four PurpleAir monitors in Grenada from January 7 to October 31, 2020.*

Characteristic	Days	Mean PM2.5 (Std Dev)	Model P-Value
Daily ship movements			0.18
0-2 (Quartile 1)	108	4.55 (2.61)	
3-4 (Quartile 2)	85	4.09 (3.02)	
5-6 (Quartile 3)	52	4.22 (3.10)	
7-16 (Quartile 4)	60	5.19 (3.58)	
Daily airplane movements			0.04
0-2 (Quartile 1)	163	4.41 (2.72)	
3-14 (Quartile 2)	70	3.93 (2.31)	
15-28 (Quartile 3)	72	5.23 (4.07)	
Present of Emergency Powers			0.02
No	85	5.19 (4.02)	
Yes	220	4.23 (2.53)	
Curfew Hours			0.17
None	200	4.40 (3.08)	
Less than 12	73	4.98 (3.13)	
12 – 24	32	3.85 (2.18)	
Saharan Dust Day			<0.001
Yes	48	8.60 (3.83)	
No	257	3.70 (2.05)	
Daily Temperature (Celsius)			0.27
22.00-27.20 (Quartile 1)	79	4.64 (3.76)	
27.21-28.00 (Quartile 2)	74	4.24 (3.08)	
28.01-28.60 (Quartile 3)	76	4.08 (2.31)	
28.61-30.30 (Quartile 4)	76	4.97 (2.74)	
Daily Atmospheric Pressure (mbs)			0.04
1009.00-1012.00 (Quartile 1)	77	3.79 (2.32)	
1012.01-1014.00 (Quartile 2)	76	4.30 (2.60)	
1014.01-1015.00 (Quartile 3)	76	4.77 (3.29)	
1015.01-1017.00 (Quartile 4)	76	5.11 (3.59)	
Daily Wind Speed (m/s)			0.01
0.94-4.56 (Quartile 1)	79	3.75 (2.35)	
4.57-5.98 (Quartile 2)	74	4.09 (2.95)	
5.99-7.00 (Quartile 3)	78	4.90 (3.45)	
7.01-10.30 (Quartile 4)	74	5.16 (3.01)	
Social Gathering Limits (not including Weddings or Funerals)			<0.01
No Social Gathering Limits	84	5.23 (4.03)	
20 people	124	3.80 (2.04)	
0 people	97	4.76 (2.95)	

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