Impacts of Sugar Cane Agricultural Fires on Air Quality in Southern Florida: Modeling Particulate Matter with the HYSPLIT Atmospheric Dispersion Model

Charles K. Wirks
IMPACTS OF SUGAR CANE AGRICULTURAL FIRES ON AIR QUALITY IN SOUTHERN FLORIDA: MODELING PARTICULATE MATTER WITH THE HYSPLIT ATMOSPHERIC DISPERSION MODEL.

By

CHARLES WIRKS

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Charles K. Wirks defended this thesis on May 23, 2019.
The members of the supervisory committee were:

Christopher D. Holmes
Professor Directing thesis

Henry Fuelberg
Committee Member

Jeff Chagnon
Committee Member

The Graduate School has verified and approved the above-named committee members, and certifies that the thesis has been approved in accordance with university requirements.
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ABSTRACT

The state of Florida annually approves $7.4 \times 10^5$ hectares ($1.8 \times 10^6$ acres) of prescribed fires, and the production of particulate matter (PM) may cause health issues for neighboring communities. Incomplete combustion of biomass leads to the production of abundant amounts of concentrated PM. PM smaller than 2.5 microns in diameter (PM$_{2.5}$), may have adverse effects on respiratory and cardiovascular health, as shown in earlier studies. Excessive exposure to PM$_{2.5}$ may lead to diseases such as respiratory distress, asthma, heart disease, cancer, and death. In this study, the distribution and effects of PM$_{2.5}$ caused by prescribed burns of sugarcane crops during the harvest season are simulated and evaluated. This research uses archived data of prescribed fires records from 2008-2015 from the FFS open burn authorizations (OBA). The fires occur during the sugarcane harvest season from Fall (October) until Winter (typically March). We simulate the concentrations of PM$_{2.5}$ from these fires using the HYSPLIT atmospheric dispersion model driven by meteorology from the North American Mesoscale (NAM) weather model. The results are evaluated against the wind, precipitation, humidity observations, emission factors, locations of fires as reported by Florida Forestry Services (FFS) and observed concentration values reported by the Environmental Protection Agency (EPA). Errors occurred due to the uncertainties and variability in emission factors, fire location, and fire size. The simulation results were then used to evaluate mortality caused by PM$_{2.5}$ from sugarcane fires in Florida.
CHAPTER 1
INTRODUCTION

Air quality is a major concern in the United States, and South Floridians worry about the accumulation of aerosol from sugarcane crop prescribed fires. Incomplete combustion due to fires is an abundant source of aerosols. Approximately 92% of the fire area in Florida is from prescribed fires. Between 2004 and 2015, Florida approved a yearly average of 1,834,769 acres of land of prescribed fires (Nowell et al., 2018). In 2017, Florida burned approximately 2.48 million acres due to both wild and prescribed fires (National Interagency Fire Center, 2018). According to the National Interagency Fire Center, Florida burns the most land out of any other state in the U.S., with Georgia being second with 1.03 million acres less than Florida. Due to most Florida fires being prescribed, the overall amount of fires decreases during times of drought due to fewer authorizations approved of burns during a given season (Nowell et al., 2018). Florida’s flat landscape with sea breezes and intermittent winds make air quality challenging to forecast (Nicholls et al., 2002). There are millions of people that live close, and in high density, to the sugarcane fire area and a high number of these individuals are susceptible to respiratory issues.

There are many ways in which fire harms health. Particulate matter (PM) sizes less than 2.5 microns (PM2.5), can enter the lungs and cause or worsen chronic diseases, such as asthma, heart disease, and cancer (Krewski et al., 2009). PM emissions vary in size due to the completeness of combustion, which may be hindered by moisture content, abundant production of ash, lack of heat, or lack of oxygen (Bodí et al., 2014). Monitoring fires from certain croplands such as sugarcane crops in South Florida are essential due to their proximity to neighboring communities.
Degraded air quality due to sugarcane fires is not a problem that is only experienced in the United States. Researchers in other countries have explored the correlation between biomass fires and hospital admissions. Biomass is any organic material that can be used as fuel. In Brazil, researchers have shown an association between hospital admissions for asthma and total suspended particulate concentrations (Arbex et al., 2007). As over 6.8 million children are affected by asthma in the United States (Bloom et al., 2013; Mehra, 2018), the impacts of burning on air quality are a particular concern. There has been a great effort in informing communities about air quality data, but there is a disconnect between linking air pollution data and health outcomes (Mehra, 2018).

Sugarcane crops are one of Florida’s major export products that provide approximately 50% of the United States sugar products (Alvarez et al., 2008). Sugarcane crops in Florida primarily occur south of Lake Okeechobee in high concentrations adjacent to three populous counties: Palm Beach County, Broward County, and Miami-Dade County. Sugarcane harvest season in Florida generally occurs from October through March. Depending on the size of the farm, there may be up to four crops harvested throughout the harvesting season. Prescribed fire is used to harvest sugarcane as it consumes the unneeded parts of the sugarcane (e.g., leaves and green biomass) while leaving the sugar-containing stalks for harvest thus reducing the volume and mass of material that must be transported and processed for production. These are large open prescribed fires that produce an abundance of smoke and aerosols. The concern of increased pollution, aerosol, and chemical transport needs to be weighed against the benefit of burning crops during harvest season.

While the agricultural sugarcane industry has managed to benefit from these fires, it is challenging to distinguish areas that have been burned, either prescribed or not, through satellite
imagery due to Florida’s rapid vegetation growth rates. Satellites, such as the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite, which is one of the imagers used to detect land, cloud, and aerosol, may take at least 1 to 2 days to capture images of the earth (Hall et al., 2016).Additionally, the temporal resolution, the spatial resolution of up to 250 meters, and high cloud coverage are some of these issues that make it difficult to find fires and burn scars. After a fire has covered an area and has consumed the fuel, it leaves a black/dark brown carbon residue of ash and charcoal which leaves a noticeable mark on the Earth, and this is considered a burn scar.

Weather is another concern in detecting fires from satellites, and Florida’s subtropical location makes it prone to weather events that obscure fire visibility from space. Florida’s climate allows farmers to have a wide variety of cropland types. Additionally, Florida’s warm, wet climate allows vegetation to overgrow and turnover faster than many other parts of the US. The benefits for Floridian farmers for all crop types are the high yield in crop production. However, the disadvantages are nutrient runoff and pollution.

Florida is a peninsula with warm waters surrounding it; to the west is the Gulf of Mexico, to the south are the Florida Straits, and to the east is the Atlantic Ocean. The warm waters from the Caribbean Sea feed continuously into the Gulf of Mexico. The Gulf of Mexico, with its strong warm currents, creates instability that can increase the probability of storm genesis and strong wind shear. During El Niño years, there is an increase in the number of storms that are formed due to baroclinic instability. Over the Atlantic Ocean, there is a persistent high-pressure system known as the Bermuda-Azores high that produces easterly trade winds. The high pressure in the Atlantic and the warm waters that convective storms occur from lead to the prevailing winds
over Florida which are predominantly from the east. All these factors have different influences on Florida’s weather and ultimately influence the effect of aerosol transport.

The Florida Forestry Service (FFS) has an extensive data set of fires that have been reported, either prescribed or found as a wildfire. For fires to be authorized in Florida, land managers must submit a request through FFS before the actual burn can take place for fires above a specific size. Burning lesser amounts of residential yard waste on private land does not require a permit, however. In Florida, the FFS and the National Weather Service (NWS) are responsible for maintaining awareness of the propagation of smoke plumes created by large fires, so that they do not endanger or hinder civil affairs and the populace. FFS will then use a simple plume model to see if there will be any interaction to sensitive areas, such as hospitals or busy roadways, and will deny a permit if there is a significant predicted negative impact.

1.1 Aerosols

Aerosols are solid or liquid material suspended in the atmosphere. Aerosols are also called particulate matter (PM) when they contain substances in addition to water (i.e., clouds are not considered PM). Aerosols are produced by biomass burns, volcanoes, vehicle exhaust, dust and dirt blown from the surface by strong winds, sea spray, biological particles, and atmospheric chemical reactions. Events such as volcanic eruptions can force PM into the high levels of the troposphere and the stratosphere. Aerosols that enter the stratosphere can reside there for a couple of years due to strong atmospheric stability and minimal entrainment. Eventually, gravitational settling and stratosphere-troposphere transport bring PM back into the troposphere from the stratosphere. Sulfates (SO$_4^{2-}$) and nitrates (NO$_3^-$) are considered a secondary inorganic aerosol that is primarily formed through an aqueous formation throughout the atmosphere (X.
Wang et al., 2012). Most aerosol mass is contained in particles with diameters between 0.1 μm to 50 μm.

The length of time that an aerosol is suspended in the atmosphere depends on the location, its height in the atmosphere, and the size of the particulate matter (Jaenicke, 1980). Particles can be removed in several ways, depending on their size and chemical composition. Gravitational settling affects all particles with larger particles depositing out of the atmosphere faster than smaller particles. Small particle deposition can accelerate when they grow by coagulating with other particles. Particles suspended in the lower part of the troposphere can be advected to the surface by turbulent eddies as dry deposition, while water-soluble particles can be scavenged and wet deposited through precipitation. Some particles that can be scavenged efficiently are water-soluble sulfates and nitrates; these reactions occur when interacting with ammonium.

One of the most significant aerosol sources globally is ocean sea spray. However, these aerosol do not have a long residence time (Torres & Duncan, 2017). Organic carbon (OC) and black carbon (BC) from fuel combustion and biomass burning represent 1.4% of all sources of aerosol. OC and BC have a residence time of five and six days, respectively. The residence time of biomass fire aerosols in the atmosphere depends on their size and can last hours up to over a week in the troposphere (Turner & Colbeck, 2009).

1.2 Climate And Weather Effects

Aerosols affect weather and climate by absorbing and scattering electromagnetic radiation (e.g., visible light, wavelength 0.4 μm to 0.7 μm) and acting as cloud condensation nuclei (CCN) (IPCC, 2012). An increase of aerosols through a column of air in the troposphere increases aerosol optical depth, which can modify weather. For example, these types of changes can alter
synoptic circulation over regions of India and may induce extreme rainfall events (Nair et al., 2013).

Anthropogenic aerosol production has global implications that are far-reaching and complex. For example, aerosols have been found to create changes in the Earth's energy budget by reflecting and scattering light (Trenberth et al., 2009). The sun emits a spectrum of light onto the earth where it will first interact with the atmosphere and then the earth’s surface. When a particle is exposed to electromagnetic (EM) radiation, it will either be scattered or absorbed (Weingartner et al., 2003). The stratosphere contains ozone which absorbs ultraviolet radiation. The exchange of energy when a particle absorbs light can change the energy level of that particle through heat, chemical reaction, or re-radiation at different wavelengths. Light can also be scattered, which merely changes the direction of the propagation of light and does not alter the energy content.

Throughout the atmosphere, there is an abundance of nitrogen and oxygen molecules which are smaller than the wavelength of blue light. Blue light interacts with nitrogen and oxygen by scattering and re-scattering while the rest of the light will continue straight to the surface. This type of light scattering is called Rayleigh scattering, while Mie scattering is light interacting with particles of a similar size as the wavelength or larger. The degree to which aerosols absorb and scatter depends on the characteristics of each particle. Aerosols such as dark soot can absorb shortwave radiation, heat the middle of the troposphere, and so alter the general circulation of the atmosphere.

The degree of light attenuation caused by aerosols through a column of air mass is quantified by aerosol optical depth (AOD). Equation 1 is Beer’s law, the absorption or scattering of radiant energy in a medium. Where I is the irradiance at a specific wavelength ($\lambda$) of spectral irradiance $I_0(\lambda)$ measured at the top of the atmosphere (Holben et al., 1998).
\[ I(\lambda) = I_0(\lambda) \exp[-\tau(\lambda)_{tot}] \]  

To obtain the aerosol optical depth, Eq. 1 is used to retrieve the total optical depth \((\tau_{tot})\) and then subtracting the optical depths due to other constituents (e.g., water and Rayleigh scattering) shown in equation (2) (Giles et al., 2019).

\[ \tau(\lambda)_{Aerosol} = \tau(\lambda)_{tot} - \tau(\lambda)_{water} - \tau(\lambda)_{Rayleigh} - \tau(\lambda)_{o3} ... \]  

AOD quantifies the solar radiation lost through the earth’s atmosphere and can be measured by satellites and ground stations where 0 is a clear sky and values such as one indicates that there is much aerosol in the atmosphere. Obtaining the AOD is useful in forecasting air quality by monitoring regions of high concentration of PM and its propagation. Aerosols can either reflect or absorb solar radiation. Many aerosols predominantly reflect solar radiation; they, therefore, cause a net negative forcing effect such that they cool the atmosphere. Aerosols such as soot and black carbon absorb solar radiation and contribute to a positive forcing in heating the atmosphere.

The process of absorption can disrupt atmospheric circulation where it may heat the middle portion of a column of air by way of altering storm tracks. The darker the color of the particulate matter, the higher the quantity of absorption, which leads to a greater energy transfer through heat. It has been studied that a large amount of aerosol production may alter storm track and intensity. For instance, the production of aerosol in Asia propagates over the Pacific Ocean and increases the AOD, decrease shortwave radiation loading, and increases longwave radiation at the top of the atmosphere (TOA). These ingredients increase eddy meridional heat flux and can be seen in an overall increase of precipitation and poleward heat flux compared to simulated conditions of the preindustrial times (Y. Wang et al., 2014).
1.3 Severe Weather Caused By Aerosols And Fire

Changes in climate can be affected directly, semi-direct, or indirectly by aerosols through aerosol radiative interactions (ARI) and aerosol-cloud interactions (ACI) as described by Li et al. (2016). Aerosols that change the direction of solar radiation either by absorbing and scattering is an adequate representative of ARI. Aerosols that have higher absorption rates change the thermodynamics of the atmosphere, which has the varying implication that will be discussed later in this chapter, this is a semi-direct aerosol effect. ACI describes the interactions of radiation on the atmosphere where aerosols act as a cloud condensation nuclei (CCN) and ice nuclei. CCN are particles that are hygroscopic and act as a surface for water vapor to condense onto to make water droplets. ACI can be considered an indirect radiative forcing such that CCN’s can alter the characteristics of clouds which will change how radiation interacts with it.

ARI, or direct aerosol forcing, interacts with the atmosphere more under clear conditions rather than overcast conditions. Under clear conditions, aerosols affect scattering equally from the top of the atmosphere to the surface. This effect is not the same for absorption since there is more absorption at the surface and little to none at the TOA. The atmosphere and the surface are being warmed and cooled, respectively, by aerosols with opposite signs, sometimes at similar rates when considering absorbing aerosols only (Ramanathan et al., 2001).

In a semi-direct regime, aerosols may lead to surface warming. In some cases, black carbon (BC) can evaporate water droplets in the atmosphere that leads to higher solar radiation reaching the surface. Another semi-direct effect contributed by aerosols is its effect on the boundary layer. Most aerosols are trapped in the planetary boundary layer (PBL). The PBL is the layer closest to the earth’s surface and is defined as an often-turbulent layer typically capped by a temperature inversion. The boundary layer characteristics will be covered in more detail in chapter 3.2.
Aerosols alter the microphysics of clouds where they can modify the amount, phase, and size of the cloud droplet or ice crystal; this is considered an indirect effect (Li et al., 2016). Aerosols can hinder precipitation, which allows a higher number of small droplets to build up before precipitation begins. Aerosols that absorb stalls convection by stabilizing the lower atmosphere and suppressing the genesis of convective clouds. However, convective perturbations that overcome this convective inhibition can become more intense as a result (Rosenfeld et al., 2008). Areas where the threshold is exceeded frequently occur in polluted areas due to the abundance of aerosols and the insufficient amount of water vapor to condensate onto nuclei. Overturning in the system induces the water vapor to condense and release latent heat to cause more overturning in a positive effect (Rosenfeld et al., 2008). The distribution of heat throughout the storm favors evaporation and cooling, which will induce strong downdrafts, forcing the ambient air upwards, thereby enhancing heat transport upward. Increased heat higher in the troposphere leads to more considerable turbulence throughout storms, which encourages precipitation and further enhances convective overturning, thus promoting vigorous atmospheric circulation.

Other severe storms that are created by aerosols in rare occasions are called pyrocumulonimbus. Severe biomass burns, such as large wildfires or volcanoes, can create pyrocumulonimbus storms. These storms are associated with substantial amounts of lightning. Similar situations are common with volcano eruptions or during significant fire events. Massive wildfires or volcano eruptions can cause a more substantial amount of heat to rise through sensible and latent heat release in smoke plumes. When biofuel combusts, water vapor can come from the chemical reaction during the combustion or by the liquid water in the biofuel that is not chemically bound to the molecules (Parmar et al., 2008). Lightning from these storms can also create more wildfire episodes worsening the situation.
1.4 Health Implication Of Aerosols

Health officials are mainly concerned with aerosols that are less than 2.5 microns in diameter due to the health implications associated with it, such as asthma and cancer (Krewski et al., 2009; Salvador & Salvador, 2012; US EPA, 2008). Most aerosols at this size are products of incomplete combustion, among other sources, and if large quantities are inhaled, the aerosol enters deeply into the lungs and circulatory system.

PM$_{2.5}$ has been linked to asthma, heart disease, and cancer, and there is a need to monitor and investigate the production and the spread of PM. Arbex et al. (2007) results show that with a 7-day cumulative effect of an increase in 10 μg m$^{-3}$ of total suspended particle concentration that there is a 9.7% rise of asthmatic related hospital admissions. This study observed 640 asthma-related hospital admissions over a 493 days period where 318 days consisted of sugarcane burns. Similar research occurred about agricultural burns such that a local region experienced an increase in PM10 concentrations from 15-40 to 80-110 μg m$^{-3}$ for 24 hours. Individuals in this region with chronic asthma and bronchitis were most affected (Long et al., 1998).

The National Ambient Air Quality Standards (NAAQS) that is regulated by the EPA sets standards for such pollutants as inhalable particles. The threshold for clean air to breath for particulate matter is for PM$_{2.5}$ to not exceed a yearly average of 15 μg m$^{-3}$ as well as a 24 hour average of 35 μg m$^{-3}$ (US EPA, 2013).

In 2010, the EPA reported that in the U.S., approximately 160,000 premature adult deaths were associated with PM2.5 exposure (US EPA, 2011). In California, between 2005-2007, the total cost of hospital care associated with PM$_{2.5}$ amounted to $193 million (Romley et al., 2012). The average exposure of the general public in California to PM$_{2.5}$ in 2018 is 11.9 μg m$^{-3}$
The average person in the United States is on average exposed to 8.4μg m$^{-3}$ (U.S. Census Bureau, 2015).

In general PM$_{2.5}$ can cause respiratory distress, asthma, heart disease, and cancer (US EPA, 2013). There are several ways in which PM may create adverse health impacts. Larger aerosol particles that enter may irritate the throat, resulting in coughing to expel the aerosol or may be ingested (Pope & Dockery, 2011). Xing et al. (2016) stated that injuries from PM2.5 could occur by free radical peroxidation, imbalanced intracellular calcium homeostasis, or inflammation to the inner wall tissue of the lungs. Free radical peroxidation can happen when a molecule such as a transition metal is carried into the body on an aerosol then causes a reaction that takes an electron from the inner organ tissue. PM2.5 can carry transition metals and different organic compounds that can trigger inflammation or immune responses throughout the body. These metals can produce hydroxyl radicals, which can cause cell damage to lipids, proteins, and DNA through a process called Fenton’s reaction (Zepp et al., 1992).

PM$_{2.5}$ may enter the lungs and into the pulmonary interstitium and cause inflammation that causes the blood to clot and leads to coronary heart disease; this is when lack of oxygenated blood traveling to the heart causes damage (Harrison & Yin, 2000). Higher levels of ambient air pollution have been associated with the production of fatty tissue in arteries, which is the process in which coronary heart disease occurs (Simkhovich et al., 2009). An aerosol in the body is a foreign object, and the body will try to eliminate that foreign body. If the body is reacting to PM2.5 in the lungs, the inflammation that occurs can be destructive and cause immediate harm.

Asthma is a chronic disease where the inner lining of the airways (bronchial tubes) become swollen, filled with extra mucus, and causes difficulty in breathing (Mummy et al., 2018). When
there is an asthmatic event, the bronchial tubes that are inflamed are then more sensitive to environmental forcing such as particulate matter which then exacerbates the event.

1.5 Clean Air Act

In 1947, California declared that air pollution is an emergency that needs to be addressed. Thus, California passed the California Air Pollution Control Act (CAPCA). This act was the first time that a control measure was put in place for a state for air pollution (Forswall & Higgins, 2005). This trend continued with other states, and they implored the federal government to take notice and act. On July 14, 1955, the Air Pollution Control Act was passed, becoming the first federal act related to air pollution (Forswall & Higgins, 2005). This act did not enforce regulation but provided $5 million annually for five years to the Department of Health Services and the Department of Health, Education, and Welfare towards research. On December 17, 1963, the Clean Air Act was put into effect, and the development of the criteria for air quality began (US EPA, 2019b).

There were three revisions to the original Clean Air Act: 1965, 1970, and 1990. One of the significant revisions in the 1965 amendment was the standards imposed on automobiles emissions. In 1970, there was a major push for standards on the state to enforce better air quality. One of the major components to the 1970 revisions was the National Ambient Air Quality Standards (NAAQS) that the Environmental Protection Agency (EPA) is responsible for regulating. The NAAQS establish an upper limit of acceptable concentrations of pollutants for outside ambient air. Particulate matter concentration standards were established on the NAAQS in 1971 and then revised in 1987.

Particulate matter was reviewed in 1987 when the EPA was focused on “inhalable particles,” defined as particle sizes smaller than 10 microns. In 1997 this was examined further, and there
was more of a focus on PM2.5. The standards set in 1997 were not to exceed a yearly average of 15 μg m$^{-3}$ moreover, a 24-hour average of 65 μg m$^{-3}$. The EPA then conducted further research and concluded in 2006 to lower the 24-hour average to less than 35 μg m$^{-3}$ where it stands today (US EPA, 2019c).

1.6 Sugarcane Crops

Sugarcane is believed to have originated in New Guinea, which has a similar humid and temperate climate to Florida, making Florida climate suitable for sugar cane to thrive (Mukerjee, 1957). Sugarcane crops in Florida are the highest net grossing agricultural income, surpassing net profits of tobacco and corn combined (UF|IFAS, 2016). Florida produces a quarter of the world’s sugar and half of the United States supply (Baucum & Rice, 2009). Florida’s agriculture industry employs approximately 1.6 million full and part-time workers in both the natural resources and food industry sectors. The agricultural sector in 2017 brought in revenue of upwards of $138 billion, where $57.5 billion was in foreign and export goods (Persaud, 2018).

Over 90% of Florida’s sugarcane crops are located on the southern side of Lake Okeechobee, the far west portion of Palm Beach County. Sugarcane is planted in late August through January. Harvesting runs from October through April with the highest yield in December (Baucum & Rice, 2009). Unlike most crops, sugarcane is burned before harvesting. Burning sugarcane crops before harvest reduces the volume of plant material that must be harvested, transported, and processed, without harming the economically valuable stalks that contain the sugar. Burning, therefore, reduces transportation and milling costs and raises profits.

Sugarcane prescribed fires remove residue and other debris that may have built up in the crops during both the off and growing seasons. Sugarcane crop residue, or the uneconomical byproduct, is known as “trash.” The sugarcane residue is made up of mostly leafy, green parts of
the plant, apart from the stalk where the sugar is concentrated. Depending on whether these leaves are attached to the stalk or not will determine the amount of PM that will be released and will also alter the amount of ash that is being produced in the fire. Farmers will burn up to 40 acres at a time, but these fires do not last much longer than 20 minutes (Baucum & Rice, 2009).

1.7 Historical Background

Farming sugar has a deep-rooted history in both Hendry and Palm Beach Counties. Sugar was revived in South Florida in the 1920s when the company General Motors’s Vice-President helped fund a declining Southern Sugar Company, which was producing 1,500 tons of sugarcane a day (Fredrickson, 1999). The high output of sugar products helped to invigorate Florida’s sugar industry. The surrounding area became inhabited with farmers that led to the growth of many of the neighboring cities. Clewiston, established in 1926, was populated by many farmers, who also brought other croplands types to the region (Heitmann, John, 1998). According to worldpopulation.com and census.gov, Clewiston had a population of 7,720 and Belle Glade of 19,667 in 2017.

Prescribed fires of these sugarcane crops occur close to populated cities. There has been recent activity regarding aerosols that these fires produce. Some groups have been fighting against current practices by pursuing stricter regulations on air quality (Marshall & Guest, 2015). Sierra Club, an environmental activist group, founded in 1892, submitted a petition in 2015 to the Environmental Protection Agency (EPA) to reevaluate the regulations in harvesting sugar in South Florida. The claims from the Sierra Club are that the regulations imposed are strictly on the mill and cogeneration plant, an energy producing plant, in Clewiston, but not on the sugarcane crops burning practices. Sierra Club asks regulators to consider the emissions from the sugarcane crop burns and reducing emissions from the plant. Their concerns are two-fold: the
release of carbon into the atmosphere and the direct health effects to the public from biomass burning.

The Sierra Club insists that agricultural practices should move to a more environmentally friendly approach. Sierra Club states that the gains for “green harvesting,” outweigh the losses. By not having regulations that directly impact extensive open area biomass burns, the situation contradicts the motives behind the Clean Air Act (Marshall & Guest, 2015). This study will try to bring new insights into the negative impacts brought on by the production of PM2.5 to local communities.

1.8 Research Goals

This work seeks to forecast PM$_{2.5}$ concentrations using the HYSPLIT dispersion model of agricultural crop prescribed fires that surround the south side of Lake Okeechobee where many fires come from sugarcane crops. The results of the concentrations will be used to evaluate the excess in mortality attributed by PM$_{2.5}$ concentrations. This research will be using the U.S. National Oceanic and Atmospheric Administration Air Resource Laboratory’s (NOAA ARL) dispersion model HYSPLIT to calculate the trajectory of the mass of PM$_{2.5}$ moreover, determine which cities it primarily affects. The importance of this research is to track the transport and dispersion of aerosol as it moves through the atmosphere, from where it starts to where it deposits, and to evaluate most affected areas.

Archived data of prescribed fires in Florida were used with records from 2008-2015 from the FFS open burn authorizations (OBA). Samples of concentration values are used during sugar cane harvest seasons which occur from Fall (generally October) and last until Winter (generally March). In this research, observed air quality data of PM$_{2.5}$ concentrations will be compared to
the simulation result in areas of most concern. With validated simulation results, we will then use said results to calculate the total excess mortality caused by PM2.5 during the years in question.
CHAPTER 2

METHODS

This project will simulate the concentrations of PM2.5 from sugarcane agricultural fires in southern Florida to assess the impact on air quality and mortality. In this section, we explain how we calculate PM2.5 emissions and plume rise for sugarcane fires (Section 2.1.2). Then, we describe the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) atmospheric dispersion model (Section 2.1.3), which simulates the emissions, transport, mixing, and deposition of smoke. Next, we describe the PM2.5 monitoring data that we will use to evaluate the model (Sections 2.2, 2.3, and 2.6). Finally, we explain the methods that relate the simulated aerosol concentrations to human health impacts (Section 2.8).

2.1 Dispersion Models

A model of the production and propagation of aerosol in the atmosphere caused by biomass burns can be created using dispersion models. The primary use of dispersion models has evolved dramatically over the past century, and it keeps advancing with more accurate tracer methods, analysis methods, and quality archival of data.

2.1.1 History Of Dispersion Models

Numerical atmospheric dispersion models emerged in the mid-20th century when military leaders wanted to predict where biological weapons were dispersed or where nuclear fallout will be displaced (Hanna, 2011). These models have evolved into sophisticated tools that are used to predict and track plumes from various sources, including industrial sources, volcanoes, fires, or nuclear accidents. HYSPLIT is a widely used dispersion model in the atmospheric community with over 2400 citations of Draxler, R. R., and Hess (1998) to date (Stein et al., 2015). HYSPLIT has been in development for over 30 years, and its origins can be traced back to the 1940s (Stein
et al., 2015). The model is commonly used to calculate simple forward and backward air mass trajectories, but also has more advanced capabilities for simulating plume dispersion. Being one of the most heavily used dispersion models in the US, HYSPLIT was deemed to be suitable for this research study.

2.1.2 Mathematics In Dispersion Modeling

Dispersion modeling is the numerical approximation of pollutant transport in the atmosphere. The “advection-diffusion” equation may be considered either in a Eulerian or Lagrangian framework. A Eulerian framework, on a fixed-grid, is represented in equation (3).

\[
\frac{\partial C}{\partial t} + \mathbf{u} \cdot \nabla C = D \nabla^2 C - D_{wet+dry}
\] (3)

The first term on the left is the local temporal change of concentration \( C \). The second term on the left-hand side is the advection term, \( \mathbf{u} \) is the velocity field, and \( \nabla C \) is the gradient of \( C \). The first term on the right side of the equation is the diffusion term, where \( D \) is the diffusion coefficient, and \( \nabla^2 C \) describes the curvature of the concentration field. Finally, \( D_{wet+dry} \) represents removal by deposition at rate \( k \). The mathematics of deposition will be covered in detail later in the chapter in section 2.1.4.

The advection-diffusion can be solved in a Lagrangian framework in which a model focuses on a parcel as it moves and changes throughout a grid. Equation (4) is the change of concentration over time due to the diffusion term and equation (5) describes the advection of the particle in the absence of diffusion or loss. Dispersion modeling is mathematically intensive, and in the next section, I will explain how many of these equations work together in simulating pollutants in the atmosphere.

\[
\frac{dC}{dt} = D \nabla^2 C - D_{wet+dry}
\] (4)
\[
\frac{dC}{dt} = 0
\] (5)

One solution under certain assumptions is the Gaussian plume equation. The Gaussian plume equation is an analytical solution to the advection-diffusion equation for a steady release of material from a point source into a uniform, constant wind field with isotropic turbulence (Stockie, 2011). The downwind plume will expand vertically and horizontally at rates that depend on the stability and turbulence of the atmosphere. The resulting distribution is

\[
c(x, y, z) = \frac{Q}{2\pi\sigma_y\sigma_z u} \exp \left( -\frac{y^2}{2\sigma_y^2} \right) \exp \left( -\frac{(z - h)^2}{2\sigma_z^2} \right)
\] (6)

In equation (6), \( Q \) (mass \( s^{-1} \)) is the source of the pollutant, \( u \) (m \( s^{-1} \)) is the mean wind, \( \sigma_i \) is the plume half-width along dimension \( i \) (Stull, 2017), which is a function of atmospheric stability and the distance the pollutant is from the source, \( x, y, \) and \( z \) are the three dimensional position vectors, and \( h \) is the height (m) at which the pollutant is released and after the initial plume rise. Most plume models attempt to simulate the dispersion from a point source that is close to the ground level. The lower edge of the plume dispersal may encounter the ground, and the reflection of the plume can be handled by adding an image source term to equation 6.

The Lagrangian particle model simulates a particle from the source, and its movement using meteorological data. In some frameworks, the particle is considered a point mass, and many particles are used to describe the pollutant distribution. In other frameworks, called “puff” models, the particle may occupy a volume that expands with time. This approach can be used for many different particles, and diffusivity rates can be calculated relative to each particle (Draxler and Hess, 1997). Unlike the Gaussian plume equation, a Lagrangian approach can simulate dispersion in the presence of differential winds and emissions. The advective motion contains a
random component that is added at each time step based on the turbulence of the atmosphere. The random element is the Brownian-like motion of the diffusivity. This random step component will yield different results each time despite identical initial conditions.

Dispersion models solve the advection-diffusion equation either in a dynamic frame of reference (Lagrangian) or in a fixed grid (Eulerian). An efficient method in computing a Lagrangian model is to incorporate both modes of computation, Gaussian puff model, and the Lagrangian Particle Model, Puff-Particle (Hurley, 1993). This computational method is a hybrid approach in which one calculates the particles in the vertical direction and the puff dispersion in the horizontal direction. The above description is the methodology of the HYbrid Single-Particle Lagrangian Integrated Trajectory, which is commonly referred to as HYSPLIT.

### 2.1.3 HYSPLIT Description

HYSPLIT is a Lagrangian transport model that calculates the advection and diffusion of particles. Although the model internally uses a Lagrangian approach, the simulated concentrations are often reported on a fixed grid. HYSPLIT solves the advection and diffusion in separate steps that represent advection by the mean wind followed by diffusion. By releasing many particles, the cloud of particles can represent a complex concentration field downwind of an emission source. Transport models use the continuity equations to compute advection. Equation 7 is the continuity equation in this process, neglecting diffusion and deposition, which will be calculated sequentially.

\[
\frac{dP}{dt} = V(P, t)
\]  

\( P(t) \) represents the position vector of a particle at time \( t \), and the three-dimensional wind velocity vector at that position and time is \( V(P, t) \) (Stein et al., 2015). HYSPLIT solves Eq. 7
with a multi-step trapezoid method, as follows. Starting at an initial position $P(t)$, a first guess
position at time $t + \Delta t$ is calculated with a forward Euler step.

$$P'(t + \Delta t) = P(t) + V(P, t) \Delta t$$  \hspace{1cm} (8)

The wind velocity is calculated again at the new position $P'(t + \Delta t)$. The new position
$P(t + \Delta t)$ is then refined by averaging the wind velocity $V$ at points $P(t)$ and $P'(t + \Delta t)$:

$$P(t + \Delta t) = P(t) + 0.5[V(P, t) + V(P', t + \Delta t)] \Delta t$$  \hspace{1cm} (9)

The trapezoidal rule is conditionally stable for linear forcing’s such as cold fronts or dry lines,
and when the time steps are small (Trenberth, 1992). To maintain numerical accuracy, $\Delta t$ is
chosen so that the advection distance per timestep is smaller than the grid spacing (Draxler and
Hess, 1997). After calculating advection by the mean wind, HYSPLIT adds a small displacement
to represent diffusion.

The final horizontal and vertical location equations contain turbulent vertical and horizontal
component terms to account for dispersion. The turbulent component is derived for particles used
is from the meteorological data. The turbulent portion is added to the mean advection velocity
component to the horizontal and vertical vector of the particle. In equations (8) and (9) $P_X$ and $P_Z$
are the horizontal and vertical position vectors, respectively. Dispersal of a contaminant in the
atmosphere is enhanced by turbulent eddy motion and advection (Stockie, 2011). The horizontal
and vertical particle position components ($P_X$, $P_Z$) account for turbulence where $U'$ and $W'$ are
turbulent velocities derived from the turbulent kinetic energy provided in the meteorological
data. Physically, what occurs is that a cloud of particles through the atmosphere at each grid-
node the particle advection position is calculated. Then at its final position, after each advection
position is computed, a turbulences parameter is added to each particle to represent diffusion.
\[ P_{x_{\text{final}}}(t + \Delta t) = P_X(t + \Delta t) + U'(t + \Delta t)\Delta t \]  

(10)

\[ P_{z_{\text{final}}}(t + \Delta t) = P_Z(t + \Delta t) + W'(t + \Delta t)\Delta t \]  

(11)

HYSPLIT can run as a puff release or particle released model or hybrid. A puff represented as a point with its mass distributed throughout a volume that has different distributions in the horizontal and vertical. The number of puffs that are being simulated in a model at any given time is computed and is defined as the puff number. The puff number is difficult to determine due to convergence and divergence of puffs in each grid cell. The puff cross section can be specified as either a Gaussian or top-hat probability distribution. A top-hat distribution is where the concentration of a pollutant is zero outside the plume and uniform inside. A Gaussian distribution is a normalized distribution over a range \(3\sigma\), where the radius is approximately twice as large as the top-hat distribution \((1.5\sigma)\). For a puff model, if a puff exceeds the size of the resolution designated at the beginning of the simulation, then the puff will divide into two smaller puffs. In particle mode, the user will select a fixed number of particles to be released (Garner et al., 2006). Simulation of aerosol production from prescribed fires uses a combination model of both puff and particle using a Gaussian puff distribution in the horizontal direction and particle simulation in the vertical direction.

HYSPLIT uses gridded wind data from numerical weather models formatted in an ARL meteorology packet format (Draxler et al., 2018). There are many options for obtaining this formatted packet. One method HYSPLIT offers to convert already collected meteorological data (i.e., North America Mesoscale (NAM) 12km continental United States (CONUS) from nomads.ncep.noaa.gov) where it is being provided on government websites. Another method is to access the data directly via the HYSPLIT GUI. Additionally, users may create their own
meteorological data provided they have the following variables: pressure at surface, pressure at mean sea level, temperature at surface, total precipitation, U-momentum flux, V-momentum flux, surface sensible heat flux, latent heat flux, downward shortwave flux, temperature at 2 m, relative humidity at 2 m, u-component of wind at 10 m, v-component of wind at 10 m, total cloud cover, U wind component (respect to grid), V wind component (respect to grid), geopotential height, temperature, and pressure vertical velocity. Also, precipitation is required for wet removal calculations.

While HYSPLIT is a Lagrangian model internally, the concentration fields produced by the simulation are usually reported on a regular grid, defined by the user. The concentration is calculated differently depending on whether the model is in puff or particle mode. For particle release mode, the particle may either have a vertical distribution or a vertical and horizontal particle distribution with a mass value assigned to each particle. HYSPLIT takes the position of all the particles that are released and converts them into a user-defined gridded concentration. In puff release mode, the puff may either have a vertical and horizontal distribution or just a horizontal mass distribution. For all vertical puff distributions, all concentrations will be calculated in top-hat mode. For a particle-puff simulation, the incremental concentration increase is calculated with particles in the vertical and puffs for the horizontal; this will be described later in this chapter.

Equation 12 is the concentration within the puff computed as a top-hat for each puff with mass (m) (Draxler, and Hess, 1997).

\[ \Delta c_{\text{gauss}} = m \left( \pi r^2 \Delta z \right)^{-1}, \quad (12) \]

where the vertical extent is \( \Delta z = 3.08\sigma_z \) moreover, the horizontal radius is \( r = 1.54\sigma_h \) of the concentration for each grid point. \( \sigma_i \) is the puff standard deviation distribution, such that \( \sigma_i \)
where i specifies whether it is in the z (vertical) or h (horizontal). $\sigma_z$ is calculated using the vertical velocity variance and the Lagrangian time scale, the same method is used for $\sigma_h$ however, it is calculated with the horizontal velocity variance. The concentration on the output grid is a summation of the concentration increment from all the nearby puffs.

In a pure particle release mode HYSPLIT releases a set number of particles designated by the user on a regular defined grid and calculates the advection. Particles are computed as a cell rather than a point. A cell is considered the point in the middle of a grid-node and has an area that is halfway from the center of the said node to the connecting node. The incremental concentration contribution to that cell is:

$$
\Delta c_{\text{particle}} = m(\Delta x \Delta y \Delta z)^{-1}
$$

The incremental concentration contribution for a purely particle model is calculated using equation 13, where it calculates the amount of mass divided by the dimensions of the cell on a grid.

The hybrid particle-puff model is a nonstandard distribution of pollutants calculated in which each puff may be distributed nonuniformly throughout a grid. In equation 14, HYSPLIT adopts the PARTPUFF approach; each puff contributes a concentration increment, r is the distance from the puff center to the grid-node (Hurley, 1993).

$$
\Delta c_{\text{Partpuff}} = m(2\pi \sigma_h^2 \Delta z)^{-1} \exp\left(-0.5 \frac{r^2}{\sigma_h^2}\right)
$$

The concentration mass is summed up at all grid points that fall within the puff extent, defined by either top-hat or Gaussian distribution, for each time step. This method is used in this research and is calculated numerically in equation 15.
\[ c_j = \sum_i \frac{m_i}{2\pi \sigma^2_{hi} \Delta z} \exp \left( -0.5 \frac{r_{ij}^2}{\sigma^2_{hi}} \right) \]

Eq. 15 is the summation of all particles with \( r_{ij} < 3\sigma^2_{hi} \) moreover, within height \( \Delta z \) of grid point \( j \). \( r_{ij} \) is the distance between particle \( i \) and grind point \( j \) and \( \sigma^2_{hi} \) is the width of puff \( i \).

### 2.1.4 Deposition

Aerosol mass is removed from the atmosphere by dry deposition and wet deposition. Dry deposition is due to advection or gravitational settling of particles, which varies in speed depending on the size of the pollutant. Turbulent eddies are the main driver for dry deposition of PM, which can vary according to local meteorology. Gravitational settling of PM, not gases, is fastest for large particles (Wu et al., 2018). In the case of wet deposition, PM is scavenged from the atmosphere by precipitation. Previous research has shown that high levels of humidity in the lower troposphere causes hygroscopic particle growth, which increases gravitational settling and thus, lowering concentration levels of PM (Michael, 2007). To estimate the amount of wet deposition, HYSPLIT uses the in-cloud scavenging ratio and below-cloud scavenging velocity from Garner et al. (2006).

HYSPLIT calculates the combined effects of wet and dry deposition by equation (16):

\[ D_{\text{wet+dry}}(t) = C(t) \]  \hspace{1cm} (16)

\[ k = (\beta_{\text{dry}} + \beta_{\text{inc}} + \beta_{\text{bel}}) \]  \hspace{1cm} (17)

\[ C(t + \Delta t) = C(t) \exp(-\Delta t \cdot k) \]  \hspace{1cm} (18)

The total deposition \( D_{\text{wet+dry}} \), which refers to the C term in Eq. (4), is defined by the remaining mass \( C(t) \) in the atmosphere, dry deposition \( (\beta_{\text{dry}}) \), wet scavenging in-cloud \( (\beta_{\text{inc}}) \), and wet deposition below-cloud \( (\beta_{\text{bel}}) \). This term will remove the mass that is in each grid cell at each time step based on the criteria above. These terms will be discussed later in this chapter.
One method of dry deposition is gravitational settling. Gravitational settling for deposition is calculated using the method by Van Der Hoven (1968):

\[ V_s = d_p^2 g (\rho_g - \rho) (18\mu)^{-1} C_c \alpha^{-1} \]  

(19)

Gravitational settling \((V_s)\) is the terminal velocity of a falling sphere under viscous Stokes drag with correction factors for a slip and non-spherical shapes. Dry deposition velocity is calculated for a spherical particle for a particle diameter \((d_p)\), air density \((\rho)\), and particle density \((\rho_g)\), where \(\mu\) is the dynamic viscosity of air \((0.01789 \text{ g}^{-1}\text{s}^{-1})\). Adjustment for the drag of a particle in a fluid is accounted for by the slip correction \((C_c)\) and the dynamic shape \((\alpha)\) for non-spherical particles. \(V_s\) is added on to the final vertical position for the pollutant at each time step to show a gradual decline. The mass is removed from the simulation when its position intercepts the ground. Although gravitational velocity contributes to the overall deposition, this value is added to the position vector of equation (9) for particles and puffs.

Explicit dry removal \((\beta_{dry}; \text{ Eq. 17})\) is where a plume in the surface layer has particles intercept and impact the surface from the bottom portion of the puff. The meteorological data that determines the extent of the explicit dry removal is usually the second level just above the surface layer. Explicit dry removal is calculated by assuming a uniform vertical concentration in the deposition layer. The explicit dry removal calculations assume a top-hat distribution in the vertical and the depth of the pollutant layer \((\Delta Z_p)\) as \(\pm 1.54\sigma_z\); this is contained in the puff calculation. The deposition is converted to a time constant where deposition velocity \((V_d)\) may be inputted, or it may be calculated as a settling velocity.

\[ \beta_{dry} = V_d \Delta Z_p^{-1} \]  

(20)

Wet scavenging in cloud \((V_{inc}; \text{ Eq. 21})\) is defined by the scavenging ratio, approximately \(S = (5 \times 10^5 \text{ to } 1 \times 10^6)\). The scavenging ratio is the concentration of particles in water versus
the concentration of particles in the air. In equation 21, the rate of precipitation (P) estimates the amount of water available in the cloud, and that precipitates out.

\[ V_{inc} = S \times P \]  
(21)

In equation 22, the removal of the mass is due to in-cloud scavenging that is independent of precipitation. For this equation, \( F^t \) is the fraction of the pollutant layer at the top of the cloud to designate how much of that layer is contributing to the pollutant mass, \( F_b \) is the fraction of the pollutant layer at the cloud base, and \( \Delta Z_p \) is the thickness of the layer of the pollutant. Another option is to input the rate constant for in-cloud scavenging directly. In-cloud scavenging is obtainable when the in-cloud velocity coefficient is less than one.

\[ \beta_{inc} = F^t F_b V_{inc} \Delta Z_p^{-1} \]  
(22)

Similar to in-cloud velocity, when the removal coefficient is directly inputted and less than one, the below-cloud intake velocity becomes a function of precipitation, where the ratio of mass to precipitation is \( S = (4 \times 10^{-5} \text{ to } 8 \times 10^{-5}) \). In this research, we used below-cloud removal as a constant, as shown in equation 24.

\[ \beta_{bel} = 1 \times 10^6 (1.0 - F_b) \]  
(23)

2.2 Fire Emission

Emissions are calculated using the bottom-up approach presented in Andreae & Merlet (2001), where pyrogenic emissions are calculated with several variables (Seiler & Crutzen, 1980):

\[ E = A \times F \times C \times e_i / D \]  
(24)

where \( E \) is the emission rate (\( \mu g \text{ hr}^{-1} \)), \( A \) is cropland burned area (ha), \( F \) is fuel load, meaning the biomass per hectare (kg/ha), \( C \) is the combusted fraction, meaning the fraction of the biomass that is burned (kg/kg), \( e_i \) is the emission factor for species \( i \) (McCarty, 2011), meaning the mass
of compound $i$ produced from combusting a unit mass of biomass, and $D$ is the fire duration. We obtained cropland burned area ($A$) from Florida Forest Services open burn authorization (FFS-OBA). FFS provides this data in acres, which converts to hectares (1 ha = 2.47 acres). Fuel load variable ($F$) was assumed to be 4.75 tons per acre, which comes from EPA data for sugarcane (Pouliot et al., 2017). Combustion fraction ($C$) is a value ranging from 0 to 1 that is directly affected by moisture content, in which if there is a higher moisture content there will be less efficient combustion and can lead to a higher concentration emission release of PM2.5 (Rahai et al., 2017).

Emission factors, such as fuel load and combustion completeness approximations, were derived from studies and government reports (Andreae & Merlet, 2001; US EPA, 1995; McCarty, 2011; MRI, 1997; US EPA, 2005; US EPA, 2008). Emission factors for specific species were obtained from several sources and combined by Andreae & Merlet (2001b). The emission factors were derived from 130 analyses and collected if there were more than one emission factor for one species where the result was given as a mean plus or minus a range. For PM2.5 from sugarcane prescribed fires, the emission factor is in pounds per ton. After combining each aspect of the emission factors, 1 ha sugarcane fire typically produces 7,577 g of PM2.5, and the median sugarcane fire size in Florida is 41.74 ha (US EPA. Air Quality System Data Mart, 2019). The total annual average PM2.5 emission is 4,270,552 kg, using the OBA to indicate the overall yearly average amount of sugarcane crops burned. The duration of the sugarcane crop prescribed fire is short yet intense. These fires come to peak intensity within a few minutes, then slowly die out with the whole burn lasting approximately 15 to 20 minutes for a 40-acre burn (Baucum & Rice, 2009). Sugarcane crop fires are approximately 30-minutes in duration for a whole crop burned.
This work uses HYSPLIT to simulate PM2.5 concentrations originating from sugarcane fires. The emission factors and criteria for sugarcane crops burn simulations are given in Table 1 (Pouliot et al., 2017). To simulate the emissions accurately, Eq. 24 was calculated for each fire. The boundary conditions include the amount of biomass burned, the location of the burn, the time of burn (which will be described in detail later), and the dimensions of the burn (the size of the area in acres). The OBA data provide the date on which a fire occurred, but not the time of day or duration. We assume that the number of fires burned a day are evenly distributed between 11:00 am and 4:00 pm. At 4:00 pm, there will no longer be any aerosols emitting; however, the simulation will continue to capture the path of the PM. The majority of sugarcane crops burned are in the field and not in a pile, so the sizes were given in acres.

<table>
<thead>
<tr>
<th>Average Area Annually</th>
<th>Fuel Load a</th>
<th>Combustion a fraction</th>
<th>PM2.5 Emission a factor</th>
<th>Combustion enthalpy d</th>
<th>Burn rate e</th>
<th>Annual PM2.5 emission e</th>
</tr>
</thead>
<tbody>
<tr>
<td>142,008 ha</td>
<td>10,648 kg/ha</td>
<td>0.65</td>
<td>4.345 g/kg</td>
<td>3.45 ± 0.21 × 10^6 J/kg</td>
<td>0.61 min/ha</td>
<td>4,270,552 kg</td>
</tr>
</tbody>
</table>

(Pouliot et al., 2017)\textsuperscript{a}, FFS-OBA \textsuperscript{b}, (Baucum & Rice, 2009)\textsuperscript{c}, (Turn et al., 2005)\textsuperscript{d}, The fire duration is $D = AR$, where $R$ is the burn rate, This research \textsuperscript{e}

The heat of combustion is a source of buoyancy for the smoke plume, which causes the plume to rise through the atmosphere. HYSPLIT accounts for buoyant plume rise using equations initially developed for emissions from industrial smokestacks (Briggs, 1975). This approach requires specifying the thermal power production (Watts), called “heat” in the HYSPLIT documentation and “emitimes.txt” file.

Thermal power of a prescribed fire is the product of the area of the fuel and the type of said fuel, e.g., sugarcane crop (Baek et al., 2009),

$$P = A F C H / D$$ (25)
Where $P$ is the heat flux ($J/s$) released for each fire. Variables $A$ (area), $F$ (fuel loading), $C$ (combustion fraction), and $D$ (duration) are the same in values as Eq. 24. $H$ is the heat content ($J/kg$), meaning the amount of energy that is released per mass of fuel combusted. The heat content ranges from $3.24 \times 10^6$ to $3.67 \times 10^6$ Joules/kg, dry fuel basis, due to the variable moisture content increasing the ash production of the sugarcane type (Turn et al., 2005). To simulate the natural variability of the environment, a random number generated between $3.24 \times 10^6$ to $3.67 \times 10^6$ J/kg for the heat content. To get plumes that vary vertically, a random choice generator will multiply the heat equation with a variable (i.e., 1, 0.1, or 0.01) to take into account the moisture content.

The rate each crop burns, in Table 1, is estimated through literature and expert knowledge in Baucum & Rice (2009). There were several assumptions made due to lack of detailed information. The main premise was that the biomass being burned was homogenous, in that that there was no other type of biomass except sugarcane byproduct, “trash.” The idea was that the emissions released were proportional to the area burned. Lastly, the burns were continuous such that fires are quick to come to peak temperature but slowly die out. In the simulation, the fires were steady in releasing emission and may show a slightly altered view of concentrations when evaluating from observations. More definitive work needs to be accomplished to find a definitive conclusion in the rate of burn. Agricultural burn emission factors had an error of 52% averaged for all PM$_{2.5}$ (McCarty, 2011). Residue crop burning had a higher level of uncertainty of emission factors when compared to the total; section 2.4 will review the uncertainties in the emission factors (McCarty, 2011). There is a nonlinear relationship when using the bottom-up method in determining emission factors due to a large amount of uncertainty and error for each emission variables (McCarty, 2011). There is a need for more work in determining the
relationship between emission factors, determining the burn area of crops, assigned crop type, fuel load, and combustion completeness to calculated emissions (McCarty, 2011).

### 2.3 The FFS OBA Data

The Open-Burn Authorizations (OBA) was obtained from the Florida Forestry service (FFS) for years 2004-2015. The data includes the location, in latitude and longitude coordinates, of every fire in Florida. The OBA database contains crop type (e.g., agricultural-sugarcane), area (if not in a pile it was in acre units), and date. The accuracy was predicated on the validity of the land managers that would request it. FFS generally issues permits when safety allows, so land managers have little incentive to burn without a permit. The state usually approves the requests, but the landowners may not burn that day for unforeseen reasons so that the data may overestimate the amount of area consumed. Past work found that the error in the area associated with the OBA is between 0.7-0.8 km, less than 20% of the fires that were reported were over 2 km from the actual burn location (Nowell, Holmes, Robertson, Teske, & Hiers, 2018). Fires reported through FFS-OBA as a point area fire for smaller fires, between 50-95% of fires, are outside of the locations burned. This oversight is a more noticeable issue when land managers combine many small fires into one location (Nowell et al., 2018).

Wildfires are fluid and may occur in many situations under several types of circumstances, which makes for a problematic predictor. FFS and other civil serving departments make finding and annotating wildfires a less daunting task. The Fire Program Analysis Fire Occurrence Database (FPA FOD; Short, 2014,2017) put together a record of wildfires from archives derived from the federal and state levels, tribes, and the private sector (Nowell et al., 2018). However, it does not include prescribed fires. This work is using data obtained by the Florida Forestry Service (FFS), and the fires that were analyzed are ones that were planned and requested through
proper channels. We infer the emissions from sugarcane fires from Florida government records. Prescribed fires in Florida require a permit, called an open-burn authorization (OBA), from the FFS. OBAs are only issued when weather conditions allow safe burning, with minimal risk of the fire to break, and when downwind smoke is unlikely to impact a community, major roadways, school, hospital, or other sensitive facilities. The OBAs annotate the date, location, area, amount of piles as well as their dimensions (i.e., pile height and pile width), and type of fire (e.g., Agricultural Sugarcane and Silvicultural hazard removal).

Some of the limitations to this data are the permits for the right to burn. Farmers and agriculturalist may submit a request to burn, but due to unforeseen circumstances may not complete such task. Other inaccuracies may come from the location of the burn such as incorrect coordinates, errors in the street address, or errors when FFS is converting coordinates to grid locations. Land managers may also request an OBA and may submit for a region that may have a large body of water located inside of it. A large body of water in the middle of a prescribed burn area will disrupt a plume calculating with an inaccurate total of area burned. Florida readily approves prescribed fires due to its moderate climate; this gives little motivation for land managers to underestimate the area burn. Florida’s high approval rate gives the notion that OBAs may overestimate the burn areas. These issues may make it difficult to simulate smoke plumes accurately.

2.4 Errors and Uncertainties

All emissions factors and heat content hold various levels of uncertainty due to errors in different input parameters such as burned areas and assigned crop type. There are a few key determinants that can influence the concentration and propagation of a plume of pollutants in the air that is monitored hourly. Most of these factors are observed at surface stations for consistent
results and easy access for maintenance. With only a surface view of the atmosphere, there is a large room of uncertainty in various constituents that may determine the lifecycle of a plume after leaving its source. This research attempts to evaluate the meteorology and its influence on the sugarcane fire plume and can only account for near-surface wind direction, wind speed, relative humidity, and precipitation. Being that this accounts for a sparse amount of data, this leaves out other vital contributors, e.g., vertical transport, vertical and horizontal eddy diffusivity, and boundary layer depth. The insufficient ways in which this research may validate the results leave a fixed amount of uncertainties that this research cannot quantify.

The area used in determining the different emission and heat rates comes from the FFS-OBS. Through the research of Nowell et al., (2018) it is found that during the years of 2004-2015 the FFS OBA contained 95.4% of the known prescribed fires, much more than is detected by satellite products, Global Fire Emissions Database (GFED) with a MODIS instrument. Per day each fire area median differed in the area between -0.4% to -13% (0.1 to 11 ha, range across our four study sites) and were characteristically smaller than requested. The error for a particular fire area is -37% to +23% of the OBA area (±20%–25% median absolute deviation). The research also investigated the study holistically, concluding it is a better evaluation of uncertainty in the OBA. The total area of burns in the OBA for 4300 fires were 504,000 ha compared with 555,000 ha that is mapped as burned; this is a 9% error. The error in the OBA is 20%–40% in an area for a given location and day, however, less than 20% in error when averaged throughout the study period for a single site and less than 10% when averaged for larger regions.

Satellites frequently have more significant degrees of variability when monitoring fires with a range in error from 40%-90% of fires throughout the southeast US with an abundance of agricultural areas (Hu et al., 2016; Zhu et al., 2017). The point locations in the OBA had median
errors of 0.7–0.8 km with less than 20% prescribed fires in the OBA were located distance
greater than 2 km away from the actual fire. This research shows that 50%-98% of the location
errors are located outside of the actual fire perimeter. Hence the FFS OBA database is reliable
for an overall dispersion of fires in Florida but not the precise position of each fire.

Variables used in determining the emission values have a moderate amount of uncertainty.
The total amount of residue burned on a crop may vary based on the amount that is available and
the amount able to burn based on moisture content and other factors. Sugarcane residue
combustion efficiency ranges from 17-65% combustion completeness (Jain et al., 2014;
McCarty, 2011). Emission factors were derived from several studies, obtained through remote
sensing and using a ‘bottom-up’ method in calculating emissions described in section 2.2. PM2.5
emission factors were obtained through research of five agricultural sites, and out of the five
different types of crops, there was a 52% error in the amount of PM2.5 produced. Out of the five
crop types, sugarcane, wheat, and rice amounted to 70% of the total error.

Our approach used fuel loading values determined by EPA literature based on the biomass
that farming experts estimate is present in a sugarcane field. Other studies (e.g., Global Fire
Emissions Database) use the remote sensing approach for fuel loading. There are a few inherent
biases in this approach, such as a model of fuel load reduction by humans and growth and decay
of fuel load after the most previous fire. The EPA used a different approach using a residue to
crop ratio due to high uncertainty in bottom-up emissions calculations. The EPA concluded
higher emission results for sugarcane fires due to a 71% higher fuel load variable (McCarty,
2011). Enthalpy of sugarcane residue calculated in a controlled environment in which a conveyor
moving sugarcane residue, dry and green, into a broiler. The enthalpy of sugarcane range in
value depending on the amount of ash produced due to contaminated water that cleaned the
green leaf material. The initial deformation point of ash, in which it starts to become liquified, were well above the deformation point of sugarcane residue. The higher the amount of production of ash reduced the combustion enthalpy, thus the higher the contaminants, the more significant amount of ash, which in turn will reduce the amount of heat generated.

2.5 North American Mesoscale Model

North American Mesoscale (NAM) meteorological data was used in HYSPLIT model dynamics in ARL format. NAM model output was used in evaluating wind direction and speed against observations. NAM was developed in 2006 and was operational in 2007. NAM analysis runs a 12 km spatial resolution with a 3-hour temporal resolution with runs at UTC, 06z, 12z, 18z for 84 hours.

Differences in accuracy in higher resolution models are generally to resolving more of the physics explicitly. NAM also has a higher 3 km spatial resolution but using the 12 km lessens the computational processing load. A model running with a relatively lower resolution may not resolve convection and must parameterize this as a sub-grid scale effect. A model running at 3 km resolution will be able to resolve convection explicitly. A large eddy simulation will be limited to resolving eddies on a scale based on the grid resolution and will parameterize the smaller scales. HYSPLIT has a built-in converter that allows users to convert meteorological data in GRIB1 format and WRF-ARW NetCDF format to the ARL packed HYSPLIT compatible format. Including a NAM 3km data can give a more accurate representation of different micrometeorology such as land-sea breeze, tornados, and convective plumes.

2.6 HYSPLIT Configuration In This Work

For this research, we use HYSPLIT in the part-puff configuration. The puffs have Gaussian distribution in the horizontal and particle distribution in the vertical. The domain for each model
run spans 30°×30° with a resolution of 0.05°×0.05°. The center of the grid is located in the center of the first emission source, and the span of the grid extends out 15° North, South, East, and West from the center. In this case, to measure the concentration of the Gaussian puff in the horizontal, Δz in equation 12 is defined as the grid-cell height, and the model ceiling was defined to be 10km. Twenty sampling levels range from the surface to 3 km and are averaged between each level. Less than 1% of PM$_{2.5}$ is found between the heights of 3-10 km. Thus, we chose 3 km to be the top sampling level. The sampling start time will be for the first year on October 1$^{st}$ and will last until the following year on March 31$^{st}$. The sampling interval occurs as an average every 30 minutes.

HYSPLIT can calculate the vertical velocity, for example, using variables such as pressure or potential temperature. However, NAM model data provides the vertical velocity field that is used in this research. We define the pollutant with a diameter of 2.5 μm, a density of 3 g cm$^{-3}$ (Shi et al., 2015), and with a spherical shape (Ganser, 1993). The characteristics of this pollutant drive the removal of said pollutants in the levels above the surface in the troposphere. The concentration in the lower atmosphere is adjusted by the deposition velocity in the lowest layer of the atmosphere. The deposition velocity is a fixed rate of 0.6 cm/SEC (Wu et al., 2018).

We are looking at the effects of the aerosols on neighboring communities; so, to reduce the computational expense, we made the particle life 24 hours. A 24-hour lifetime means that once the particle is emitted, it will stay active in the simulation for 24 hours then be removed. The mixing depth was calculated through the meteorological input, and the minimum was set to be 250 m. The stability of the day time boundary layer was derived from wind and temperature.

Fires that span large areas tend to have ignition points and spread gradually over an area unless impeded by terrain or blocks such as fire breaks, for instance, a gap between vegetation
where fire does not catch readily. In a wildfire, an area of land does not ignite simultaneously; it will gradually cover the area, and the peak intensity of the fire occurs shortly after ignition. To not get erroneous values, there were 2,500 particles emitted for each fire with a maximum of 150,000 particles at any time in the simulation. If there were not enough particles emitted in the simulation, there would be large values of mass assigned to the individual particles to make up for the lack of aerosols suspended. If one of these particles with more considerable amounts of mass passes over an observation station, then there will be a brief, extreme spike of aerosol concentration in the simulation. Hence, when emitting aerosol, there is a need to emit enough particles to model the smoke dispersion in the atmosphere accurately. However, emitting too many particles will make the simulation computationally expensive.

2.7 EPA and FAWN

The observed meteorological data from the EPA and through the Florida Automated Weather Network (FAWN) was used in this research. The EPA monitors and collects data on air quality around the United States with records dating back to 1999 for PM2.5 non-FRM (Non-Federal Reference Method) and 2008 for PM2.5 FRM and Federal Equivalent Method (FEM). Fine particle collection FRM is defined by its setup and how it operates outlined in EPA regulations at 40 CFR 50 Appendix L (Noble et al., 2001). EPA observed concentration values are then stored and available to the public (aqs.epa.gov). The monitoring sites measure hourly average concentration values.

FRM collects a 24-hour sample on a filter, with a known flow rate the filter is weighed on a microbalance in a lab and the concentration is extrapolated. FRM air quality stations that monitor PM2.5 use a tempered element oscillating microbalance (US EPA, 2000), which directs air in such a way that it filters out aerosols higher than 2.5μm in diameter. Aerosols then migrate onto
a patch of oil that is connected to a tempered glass that has a circuit attached to it. This electrical circuit releases a charge which creates a resonant frequency. The frequency is dampened if there is greater mass or increases when there is less mass. The amount of air is measured as a constant flow of L/min. The resulting concentration is the amount of mass in micrograms divided by the amount of air mass in meters squared. The frequency that this glass resonates is interpolated into the amount of mass that is on it. The method for the FRM is the same process for other stations that are equivalent classes I & II; however, they may differ in frequency and sample rates (Noble et al., 2001). For FEM class III, the collection method may be different, e.g., beta attenuation.

The station that was located at Belle Glade was a FEM class III beta attenuation station (Met One Instruments, 2010). The height of the FAWN data is sampled in the human “breathing zone” between 2 and 15 meters. The instrument is at approximately 9 meters, and the anemometer is above the device, where the NAM data is at 10 meters. This station used the same inlet from particulate matter to retrieve samples of PM2.5 and funnels the gas through a series of tubes. The PM2.5 measurement occurs in a chamber where a small amount of carbon-14 emits beta radiation (electrons). The tubes direct the aerosol into a chamber, using a sorting cyclone with centrifugal force to obtain the proper mass of particles (Fu et al., 2017), where there is a detector that reads the attenuation of the beta particles when the aerosol passes through it. The temperature, relative humidity, and barometric pressure are measured to obtain the corrected amount of air mass that flows through the station. Every 24 hours the amount of mass and the volume of the air is calculated, the mass is divided by the air mass to get units of μg m⁻³.

FRM and FEM stations are mainly used in counting the mass concentration of particles. The correlation (R²) between the FRM and the FEM stations are reasonable, ranging from 0.7 – 0.9 (Clements et al., 2017). The FEM stations perform well independently with few exceptions.
Most stations, either FRM or FEM, have issues when detecting values concentrations over 200 \( \mu g \ m^{-3} \) moreover, when PM reaches a lower boundary limit in the range of 0.3 to 1 \( \mu g \ m^{-3} \).

2.8 Air Quality Impact On Morbidity And Mortality

This work seeks to quantify the impact of sugarcane prescribed fires and its effect on air quality. Poor air quality mainly affects the vulnerable, such as infants and the elderly. This research attempts to quantify the impact of prescribed burns and its effects on the surrounding population by associating mortality with biomass burning air pollution by using health impact functions (Anenberg et al., 2010). We want to relate the simulated concentrations of PM2.5 that were derived in HYSPLIT to human health impacts.

We follow standard methods for quantifying the mortality effects of air pollution, as done by Anenberg et al. (2010). In quantifying the health impacts, a log-linear health function can be applied. Past research has found that the relative risk (RR) is an exponential function of pollutant concentration.

\[
RR = \exp(RF \times C)
\]  \( \text{(26)} \)

Where \( R \) is the relative risk, \( RF \) is the concentration-response factor (CRF) obtained from epidemiological studies, and \( C \) is the change in air quality, and this study will be the concentration calculated in HYSPLIT. Relative risk expresses the likelihood of death (or another health outcome) relative to a person not exposed to \( C \). \( R = 1 \) means no change in risk. If the relative risk is elevated to 1.1, then there is a 10% increase in the risk of the designated outcome, such as death. Conversely, if the relative risk is at 0.9, then there is a 10% decrease in risk. \( AF \) is the attributed fraction of mortality (or other health outcomes) that is caused by exposure to \( C \).

\[
F_A = \frac{RR - 1}{RR} = 1 - e^{-RF \times C}
\]  \( \text{(27)} \)
The attributed factor is the portion of the burden that a disease contributes to a population. The excess in mortality can then be calculated using air pollution near the population.

\[ \Delta M = B \times F_A \times P \] (28)

The mortality rate is calculated by multiplying the fraction of the baseline death rates caused by a given change in concentration categorically named the attributed factor by the population and the baseline mortality rate. B is the baseline mortality rate that refers to the rate of individuals that are due to all causes, \( F_A \) is the attributed factor, and \( \Delta M \) will be the change in mortality due to air pollution (Anenberg et al., 2010). P is the population; this data was obtained through Federal Census data that is compatible through ArcGIS. The population data is categorized into census blocks, which are finer resolution than counties. We use the statewide average mortality rate for Florida, which was 680.9 per 100,000 in 2015 (Florida Department of Health, 2019), and neglect geographical variation in the baseline mortality. The CRF for PM2.5 is estimated to be 0.006 (µg m\(^{-3}\))\(^{-1}\). The CRF value for PM2.5 means that 10 µg m\(^{-3}\) increase in ambient PM2.5 raises the risk of death, Eq. 26, by 6% (Huang et al., 2017).
CHAPTER 3
RESULTS AND DISCUSSION

The research goal is to simulate the concentrations of PM2.5 resulting from sugarcane agricultural fires in southern Florida and assess the impact of these fires on air quality and public health. This goal requires knowing the spatial distribution of aerosol in relation to the population. In this section, we assess the performance of the NAM 12 km meteorology that is used to drive HYSPLIT. Next, we compare the simulated PM2.5 concentrations to observations and evaluate the emission factors, plume rise, and other environmental factors. Next, we show which areas and populations are most affected. Finally, we will estimate the impact of simulated concentrations on human health.

3.1 Assessment of NAM Meteorology Near Sugarcane Fires

The NAM 12km meteorological data was assessed against the FAWN observations in Belle Glade. The city of Belle Glade observation site was used due to its proximity to the sugarcane crops. The parameters compared were ones that would have the most amount of influence on smoke plumes and that were accessible by monitoring stations at the surface.

In figure 2, we show the wind roses for each harvest season. The roses consist of a wind direction component in a percentage of how long the winds were in a direction and a wind speed component (m s\(^{-1}\)) that are represented with colors corresponding to the velocity of the wind. The wind rose figures are sampled throughout the sugarcane harvesting season only (October-March). The observed data shows that winds were moderately high, compared to the seasonal average. The observed winds averaged 4 m s\(^{-1}\) and were under 8 m s\(^{-1}\) for 55% of the season.

The wind direction throughout the season is predominantly easterly to northeasterly in both the model and observations. Wind directions are consistent in all years. Winds from west and south are infrequent in both model and observations. The simulated peak winds are represented
well in NAM. Some years (2011-2014) have slightly higher wind speeds, and NAM captures this.

Table 2 presents the correlation (R) between the observed and simulated meteorological conditions and its significance (P). We compared wind direction, wind speed, relative humidity, and precipitation for the harvest season using hourly data for all hours of the day and night. The range of the correlation coefficient for wind speed is 0.6-0.9 with a median of 0.9. The correlation of wind direction is 0.7-0.8 with a median of 0.8, RH is 0.8-0.9 with a median of 0.8, and precipitation is (-0.1)-0.7 with a median of 0.5. Wind speed, wind direction, and relative humidity are highly significant with all P-values less than 0.001. Thus, the simulation is sufficient in reproducing the wind and RH, but does poorly in forecasting precipitation, at least on hourly time scales examined here. After evaluating the NAM model, we concluded that the meteorological data is sufficiently in agreement with observations, although the discrepancies could degrade the HYSPLIT simulation.

Table 2. Correlation (R) of meteorological observations at Belle Glade during sugarcane harvest season with NAM simulation and significance (P) of the correlation

<table>
<thead>
<tr>
<th>Years</th>
<th>Wind Speed (R)</th>
<th>Wind Direction (R)</th>
<th>RH (R)</th>
<th>Precipitation (R)</th>
<th>Precipitation (P)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>0.6</td>
<td>0.8</td>
<td>0.8</td>
<td>0.6</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>2009</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.7</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>2010</td>
<td>0.9</td>
<td>0.8</td>
<td>0.8</td>
<td>0.5</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>2011</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.5</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>2012</td>
<td>0.9</td>
<td>0.8</td>
<td>0.9</td>
<td>-0.1</td>
<td>0.08</td>
</tr>
<tr>
<td>2013</td>
<td>0.9</td>
<td>0.8</td>
<td>0.8</td>
<td>0.02</td>
<td>0.8</td>
</tr>
<tr>
<td>2014</td>
<td>0.9</td>
<td>0.7</td>
<td>0.9</td>
<td>0.2</td>
<td>0.004</td>
</tr>
</tbody>
</table>

*All correlation values for wind speed, wind direction, and relative humidity (RH) had a significance value (P) <0.001, so only the significance for precipitation is shown.*

There are other meteorological factors that we cannot easily evaluate that influence PM2.5 concentrations in the atmosphere, such as vertical wind velocity and eddy diffusivity. These variables are not measured in the monitoring stations at the surface, as described in section 2.4.
Having little data with only a few key observation sites that enable us to validate the results gives this research a narrow view on the influencers of the distribution of PM2.5. The wind can rapidly alter the direction of the plume and diffuse concentrations if there is a strong wind shear present. PM may diffuse more readily.

### 3.2 Evaluation of Simulated PM2.5 Concentrations

Table 3 shows the location and time of operations of each EPA observation site, where the model was evaluated. The EPA PM2.5 aerodynamic monitor was covered in section 2.3. Seven observation posts were used to evaluate the simulated PM2.5. The fires generally occurred on the furthest west portion of Palm Beach County near the city of Belle Glade, as shown in Figure 1. The Belle Glade station operated until 2013 and measured PM2.5 as well as total suspended particles (TSP). This station was in operation until it was shut down and an FRM station opened east, near the coast. From 2012-2015 the location has been in Royal Palm Beach, Florida, which is located 44 km east, outside the sugarcane fire area.

<table>
<thead>
<tr>
<th>Location name</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Years in operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle Glade</td>
<td>26.72</td>
<td>-80.67</td>
<td>2008-2012</td>
</tr>
<tr>
<td>Royal Palm Beach</td>
<td>26.73</td>
<td>-80.23</td>
<td>2012-2015</td>
</tr>
<tr>
<td>Sarasota</td>
<td>27.29</td>
<td>-82.51</td>
<td>2008-2010, 2012-2015</td>
</tr>
<tr>
<td>St. Lucie</td>
<td>27.17</td>
<td>-80.24</td>
<td>2008-2010</td>
</tr>
</tbody>
</table>

Source: US EPA. Air Quality System Data Mart, 2019; Florida Department of Environmental Protection, 2017

Figure 3 shows the number of acres burned daily. Daily fire area rises approximately in the middle of October and decreases approximately at the beginning of March. Typically, 2000-3000 acres of sugarcane are burned daily during the harvest season. Figure 3 also shows the simulated and observed PM2.5 concentrations, averaged daily between the hours of 11:00 am and 5:00 pm.
We show results only for these midday hours because that is when most fires occur, and the HYSPLIT model is not expected to perform well at night, because it neglects other aerosol sources. As shown in Table 4 and Figure 3, Belle Glade had a seasonal average of 6-9.5 μg m⁻³ from 2008-2012, with spikes up to 20 μg m⁻³. The observed concentrations, from 2012-2015, in Royal Palm Beach had an ambient background of 5.6-6.6 μg m⁻³ with spikes up to 17 μg m⁻³.  

The magnitudes of the spikes in concentrations shown in Figure 3, comparing HYSPLIT and the observations, are rarely equal. HYSPLIT has much higher concentration spikes than observations in all years. Belle Glade, 2008-2012, shows large spikes in concentration irregularly throughout the harvest season and are not always correlated to total acres burned that day. Hence, the total acres burned each day is not a simple indicator of whether there will be a large spike in concentration. At Royal Palm Beach, the measured ambient PM2.5 levels are lower than was seen in Belle Glade: 5.9 and 8.1, respectively. Royal Palm Beach site is found outside of the sugarcane fire area, and this is apparent in the higher frequency of zero values in concentration predicted in the time series in Figure 3. The majority of the nonzero HYSPLIT values are larger than the observations. However, there are few spikes in HYSPLIT that exceed 50 μg m⁻³, which is comparable to the highest observed values. The wind roses, in Figure 2, show that there were low amounts of winds that came from the west, this is evident in the frequency in winds from the East and may link the low concentration values in Royal Palm Beach.

Table 4 shows the seasonal daytime average concentration for each harvest season from the HYPLSIT simulation and observation. HYPSPLIT ambient PM2.5 concentrations in Belle Glade range from 6.1-53 μg m⁻³ with an average of 20 μg m⁻³ in years 2008-2012. HYPSPLIT ambient PM2.5 concentrations in Royal Palm Beach range from 2.2-4 μg m⁻³ with an average of 3.2 μg m⁻³ in years 2012-2015. The spikes in concentration for the model for the site in Belle
Glade range from 0-127 μg m\(^{-3}\), spikes in concentration intermittently occur at the same time as the observation values. The temporal resolution for sampling was the average captured every 30 minutes. Each simulation lasted six months, October 1 through March 31, which encompasses the vast majority of sugarcane fires. The mean concentrations for both the simulation and the observations are close in value, despite the disagreement in which day or hour spikes occur.

Table 4. Observed and simulated daytime mean PM2.5 during the growing season, Belle Glade and Royal Palm Beach

<table>
<thead>
<tr>
<th>Start Year</th>
<th>HYSPLIT mean (μg m(^{-3}))^a</th>
<th>Observation mean (μg m(^{-3}))^b</th>
<th>Correlation (R)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle Glade</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2008</td>
<td>53</td>
<td>6.0</td>
<td>0.0005</td>
</tr>
<tr>
<td>2009</td>
<td>15</td>
<td>8.7</td>
<td>0.01</td>
</tr>
<tr>
<td>2010</td>
<td>10</td>
<td>9.5</td>
<td>0.004</td>
</tr>
<tr>
<td>2011</td>
<td>6.1</td>
<td>8.0</td>
<td>0.07</td>
</tr>
<tr>
<td>Royal Palm Beach</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2012</td>
<td>2.2</td>
<td>6.6</td>
<td>0.07</td>
</tr>
<tr>
<td>2013</td>
<td>4.0</td>
<td>5.6</td>
<td>0.03</td>
</tr>
<tr>
<td>2014</td>
<td>3.5</td>
<td>5.6</td>
<td>0.07</td>
</tr>
</tbody>
</table>

Source: ^aThis research, US EPA. Air Quality System Data Mart 2019^b | Belle Glade site (2008-2012), Royal Palm Beach (2012-2014)

Table 4 reports the Spearman correlation between the observed and simulated PM2.5 concentrations. The Pearson method evaluates the linearity of the variables with proportional changes where the Spearman rho correlation is based on the ranked value and not the values themselves (Hauke & Kossowski, 2011). We use the Spearman rank correlation to evaluate the simulation against the observations to see if the rise and fall of concentrations happen concurrently. The Pearson methods test for a linear correlation, which we know will be poor because the model's spikes are too high. In Table 4, we present the correlation between the simulation and the observations. The correlations range from 0.0005 to 0.07, with a median of 0.03. The years with the highest correlations are 2011, 2012, and 2014, but the values are still low.
Figure 4 shows the concentrations of PM2.5 from the surface up to 9 m, which is the first layer in the HYSPLIT model. Each panel represents one harvest season ranging from 2008 through 2015 and an average of all seasons combined. For the simulation figures of PM2.5 concentration above ground, 0 – 9 meters, the highest values are located near the fires ranging from 2 – 20 μg m$^{-3}$. Over the sugar-growing region, the multi-year average (2008-2014) concentration is about 2 μg m$^{-3}$ in the harvest season (Fig. 4, last panel). Concentrations decrease with distance from the fires and are 0.5-1 μg m$^{-3}$ over the coastal urban areas of South Florida. Differences between Table 4 and Figure 4 (last panel) are due to the sampling method; Table 4 is the daytime seasonal averages, while Figure 4 is the total seasonal average, including night time concentrations.

In Figure 4, the layer just about the surface, 0 – 9 m, there is a second local maximum of concentration over both the Atlantic Ocean and the Gulf of Mexico. The particulate matter that is east, over the ocean, appears to have a reasonable gap from the land that extends several miles east where the concentrations increase again. A sea breeze effect may be the cause of the area on the coast of insignificant PM2.5 values; this also may be an effect of surface interaction. During the research period, the climate had shown signs of a strong La Nina, which will cause the southeastern portion of Florida to have anomalously low precipitation rates (O’Brien et al., 1999). In 2010/2011, over the southeast portion shows an artifact of relatively high concentrations, this is believed to occur due to relatively drier conditions.

In Figure 4, we included the layer just above the surface up to nine meters on account of the observation meteorological post heights and the sampler height (Met One Instruments, 2010; UF|IFAS Extension, 2019). The observation sites in locations other than Belle Glade show a much higher concentration value than the HYSPLIT model (Table 4). This is due to other
sources of PM in coastal urban areas. The simulation only accounts for the PM2.5 sources from sugarcane fires. The simulated concentration values for the level above the surface drop substantially, and this shows that the observed concentrations being a much larger value. Deposition in figure 4 shows high concentrations near the areas where the fires occurred. These highest values are closest to the center of the fire area and the average values occurring on the outer limits of the fire area. Wet and dry deposition are both proportional to the PM2.5 concentrations in the overlying air, so deposition and concentration patterns are similar.

Figure 5 shows the vertical cross-section of the distribution of PM2.5 from the surface to 3km. The PM2.5 averaged between latitude 26.45° N and 26.75° N, approximately the span over all prescribed fires, where the Belle Glade station is between the latitude parallels. The longitude ranges from 79.7° W, just off the east coast of Florida, to 82.5° W, further into the Gulf of Mexico. The general distribution of PM2.5 is located directly above where the fires occurred ranging from 80.2° W, the western border of Palm Beach County, and spanning to 81.2° W, the longitudinal center of Hendry County, with higher concentrations over Belle Glade. Smaller PM2.5 concentration values span over the total of Florida and meet a boundary over the water where the concentrations values diminish. The spike in concentration over the bodies of water occurs at the first layer just above the surface, 0 – 9 meters. The graphs show the trend in PM2.5 spikes, the horizontal distribution, and the vertical distribution.

The boundary layer depth has a strong influence on the surface concentrations of aerosol. Evaluating the proper distribution of aerosol in the atmosphere can be accomplished through the height of the atmospheric boundary layer. The atmospheric boundary layer is the shallow layer of the troposphere that is in contact with the surface and is often turbulent and generally capped by a temperature inversion (Stull, 1988). The turbulence in the boundary layer mixes the PM,
which then homogenizes and dilutes the concentration as the boundary layer deepens. The boundary layer occurs throughout the globe and has varying height depending on the stability and winds just above the surface. The height of the boundary layer was determined using the potential temperature ($\theta$) profile calculated from variables in the NAM model output. The potential temperature is defined as (Holton & Hakim, 2012)

$$\theta = T \left( \frac{P_0}{P} \right)^{\frac{R}{C_p}}$$  \hspace{1cm} (29)

Potential temperature is calculated using a temperature (T) profile, the reference pressure (1000 hPa, $P_0$), a vertical pressure profile (P), the gas constant for dry air (R), and specific heat capacity at constant pressure ($C_p$). Specific heat is retrieved by the sum of the internal energy per unit mass and the gas constant of dry air, where $C_p = 1004 \text{ J kg}^{-1}\text{K}^{-1}$ moreover, $R = 287.058 \text{ J kg}^{-1}\text{K}^{-1}$. In order to determine the planetary boundary layer, potential temperature ($\theta$) with respect to height was analyzed. To look at the boundary layer, we took the mean of $\theta$ between 79.7° W and 83° W over 26.72° N, Belle Glade PM$_{2.5}$ observation post. We identify the boundary layer top as the location with the sharpest potential temperature gradient in the lowest 3 km. We expect that most of the aerosol should be below that point. We obtained an average of the meteorological data for all the seasons from October through March, day and night, and noted that the top of the boundary layer is commonly 1500 meters. We find that the layer between 1-1500m contained 73.9% of the aerosol. The layer 1500-3000m contained 25.9% of the total aerosol and 99.8% of the aerosol is below 3km.

3.3 Relative Risk of PM2.5 Exposure

In this section, we discuss a method to evaluate the mortality attributed to PM2.5 exposure using the HYSPLIT dispersion model and the mortality in the surrounding area and regions outside the where sugarcane fires occur. Figure 6 shows the population density in South Florida,
with Figure 7 focused on Belle Glade. The data are from the U.S. Census Bureau from the 2010 Census (2017 TIGER/Line Shapefiles (machine-readable data files) / prepared by the U.S. Census Bureau, 2017). There is a higher density of population closer to the coast, where the major cities in South Florida are located, with smaller towns further inland. Clewiston and Belle Glade are the largest communities inland nearby the sugarcane growing region. In these two regions, there is a more substantial presence of farmers and farm workers. Figures 8 & 9 show the simulated concentration of PM2.5 in each census block. Concentration values over the municipalities were obtained by locating the centroid of each census block (polygons in ArcGIS) and finding the mean of each HYSPLIT grid that is within 0.05 degrees in any direction of that centroid.

Figures 10 & 11 display the excess mortality in each census block, calculated with the methods discussed in section 2.8. Relating the values of PM2.5 exposure to risk is an important task that may help avert unnecessary injury and death. Relative risk was an evaluation of ischemic heart disease and cardiopulmonary heart disease brought on by exposure to PM2.5 from sugarcane fires (Krewski et al., 2009). We find that mean excess of mortality from sugarcane PM2.5 is $1.77 \times 10^{-3}$ deaths km$^{-2}$ yr$^{-1}$ for areas most affected between 26° N and 27.8° N over Florida. The annual mortalities averaged over 2008-2015 that is attributed to PM2.5 caused by sugarcane prescribed fires amounted to 57 deaths in the entire region under investigation. The sugarcane-growing region where the prescribed fires take place contributed just two of the total deaths in South Florida. Therefore, the remaining 55 deaths occur in coastal communities outside the sugarcane growing area.
CHAPTER 4
DISCUSSION AND CONCLUSION

In this research, we developed a model of smoke dispersion from sugarcane agricultural fires using HYSPLIT. Emissions are based on Florida government Open-burn Authorizations. We then simulated the distribution of smoke and evaluated it at a few key locations to assess the validity of the simulation. The model was able to predict the mean levels of concentrations of smoke but did a poor job at simulating concentrations for a given day. We examined uncertainties that could contribute to model error, including meteorology and emissions. Another variability comes from various sources such as location and size of the fires, the emission factors, the heat content, and the assumptions that were made in simulating the fires (i.e., times of ignition). We find that 12km NAM meteorology has a good correlation with observed surface wind speed, wind direction, and relative humidity. While this suggests that meteorological data is a small source of model error, there are other aspects of meteorology that affect smoke dispersion that we are not able to evaluate. Different meteorological variables include vertical wind profiles and eddy diffusion rates. Nevertheless, fire emissions are likely a more substantial source of model error in PM2.5 concentrations.

Our simulations suggest that sugarcane fires are responsible for about 2 µg m$^{-3}$ of PM2.5 over a large region south of Lake Okeechobee during October-March, the harvest season. The contribution drops to 0.5-1 µg m$^{-3}$ over most of the coastal cities in southern Florida. This is consistent with past studies of total PM2.5 exposure among Floridians. According to the United Health Foundation (2018), an individual in Florida currently is exposed to an average of 7.1 µg m$^{-3}$ of PM2.5 daily, an individual in the United States experiences 8.4µg m$^{-3}$ daily. Ambient concentrations in the United States have been decreases in recent years. Our simulated
PM2.5 concentrations are lower than observations, but only account for the aerosol from sugarcane fires, however, there are numerous other sources of PM2.5. Mugica-Alvarez et al., (2017) estimated sugarcane-burning emissions in Mexican municipalities and reported exceedances on PM2.5 with an average of 86 ± 22 μg m⁻³, compared to our results with a yearly daytime average of 18.5 μg m⁻³ in the Belle Glade area. Their research used AERMOD on Sugarcane open-area burns taking place in rural and nearby urban areas, within 3.2 km from monitoring sites. This research simulated sugarcane open-area burns with monitoring sites in the burn area and up to 44 km away. Our simulated concentration values are less due to simulating dispersion over a much larger distance from the fire source and error in emissions.

Our work estimated that smoke from sugarcane fires causes 57 deaths southern Florida, with most of those in populated coastal regions. In a recent study, Cromar et al. (2018) reported that air pollution caused 67 deaths statewide in 2016 (95% confidence interval: 1 to 146). Their assessment uses a relative risk analysis, such as this study, to determine the amount of mortality. However, their study quantified only the deaths from exposure in excess of the NAAQS (15 μg m⁻³), so they likely substantially underestimated the mortality effects of PM2.5 in Florida.

A study in Brazil shows that with a 7-day cumulative effect of an increase in 10 μg m⁻³ of total suspended particle concentration that there is a 9.7% rise of asthmatic related hospital admissions (Arbex et al., 2007). Over 60% of ambient PM2.5 was attributed to sugarcane residue burns where a populated city in Brazil was between 1 – 4 km away from the burn area. (Cançado et al., 2006). In contrast to this study, the city of Belle Glades is in the burn area for Florida sugarcane fires. The risk of adverse health effects increases daily with the increase in ambient PM2.5 concentration. Throughout the entire harvest seasons in Brazil, the average PM2.5 concentration was 16.1 μg m⁻³. The number of hospital admissions during their sugarcane
harvest season was 673 individuals that were admitted for respiratory issues, where 398 were children (Cançado et al., 2006).

There is an environmental activist group, Sierra Club, in Belle Glade that claims there is an overproduction of aerosol due to the prescribed sugarcane fires in the neighboring cities. Citizens from surrounding areas in Belle Glade have reported that during significant fire events ash can be seen scattered about the city. The regulations imposed on open fires are not at the same capacity as regulations for the sugar mill, cogeneration refineries, and other energy-producing refineries. The Sierra Club has petitioned the EPA to revisit their regulations to impose more strict guidelines not to put neighboring communities at a health risk.

Sierra Club is part of an initiative to create options for disposal of the sugarcane residue to include tilling, recycling the material into paper and cardboard, using the mulch to counteract subsidence, and burning the leaves as biomass for energy use. Sierra Club is looking to get behind their community to put an end to open field burning and stop the sugar growers from profiting at the expense of public health. In this research, we presented evidence that burning sugarcane residue contributes on average 2 μg m$^{-3}$ of concentration of PM2.5 in South Florida. A 2 μg m$^{-3}$ contribution of PM2.5 is a significant amount to the overall annual average PM2.5 level experienced by Floridians, which is 7.1 μg m$^{-3}$ (United Health Foundation).

In our research, considerable uncertainty occurred in the locations, sizes, and times of ignition, these simulations give us a general view of the amount of aerosol being emitted a day. Although our model underperformed, we can show an approach to calculating the burden of PM2.5 on mortality. We estimated there were 57 deaths attributed to PM2.5 exposure averaged for each year throughout the years 2008-2015. Most deaths are happening outside the region where sugarcane fires occurred, two deaths being in the burn area.
Future research in this area would receive help from added PM2.5 monitoring sites. There are several PM2.5 observation sites throughout South Florida. The station that was in Belle Glade was shut down, and one started operation in Royal Palm Beach. Currently, there are no stations nearby the sugarcane crops to accurately monitor air quality during these events. In regions where the atmosphere is highly dispersive, near the coastline in Florida where sea breezes are frequent, the further each fire are from the monitoring sites the amount of PM2.5 concentration will be exponentially reduced. Further research in estimating emission factors for different types of crops may assist in adequately simulating agricultural prescribed fires. There is much improvement needed in the practice of requesting approval and annotating precise locations and size of open burns in Florida. If there is not an accurate location of the fires, then there will be significant uncertainty in estimating the amount of concentration of PM2.5
Figure 1 Sugarcane prescribed fire requests 2010
Figure 2 Wind rose at Belle Glade, Fl 2008-2015, October-March, hourly sampling period.
Figure 2 Continued.
Figure 2 Continued.
Figure 3 Time series of PM2.5 Concentration (observed and simulated) and acres burned from 2008-2015
Figure 3 Continued
Figure 3 Continued
Figure 4  Simulated October-March PM2.5 deposition (left column) and concentration in the layer 0-9 m above ground level (right column). Panels show results for individual years and averaged over all years.
Sugarcane Harvest Seasonal Average PM2.5 ‘11/’12

Sugarcane Harvest Seasonal Average PM2.5 ‘12/’13

Sugarcane Harvest Seasonal Average PM2.5 ‘13/’14

Figure 4 Continued.
Figure 4 Continued.
Figure 5 Vertical cross section of PM2.5 from October-March over Belle Glade, FL 2008-2015
Figure 5 Continued
Figure 5 Continued
Figure 6 Population of census blocks in 2010.

Figure 7 Population of census blocks surrounding Clewiston and Belle Glade in 2010.
Figure 8 The average annual increase in PM2.5 concentration over South Florida due to sugarcane fires 2008-2015. Concentrations are from the HYSPLIT simulations in this work, interpolated onto the census blocks.

Figure 9 Same as the prior figure, but focused on Clewiston and Belle Glade
Figure 10  Excess annual mortality due to PM2.5 from sugarcane fires in 2008-2015

Figure 11  Same as the prior figure, but focused on Clewiston and Belle Glade
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BIOGRAPHICAL SKETCH

Charles Kenneth Wirks was born on May 11th, 1987 in Miami, Florida. He began serving in the Florida Army National Guard on October 14th, 2004. Throughout his time in the Florida Army National Guard, he reached the rank of Staff Sergeant. Charles served on three combat tours where he was awarded an Army Commendation Medal and the Naval Achievement Medal for accomplishments during his deployments in Iraq and Africa. Charles deployed to Africa in April 2016 just at the end of his time in obtaining his Bachelor of Science degree. During these tours, Charles served as a squad leader and team leader in an Infantry unit. He currently is serving in a Military Intelligence unit as a squad leader.

Charles Wirks received his Associates Degree at Broward Community College in May 2014 in General studies. He then went on to earn his bachelor’s in science degree in Geoscience with his concentration in Atmospheric Science with a minor in Mathematics from Florida International University in May 2016, amid his pre-deployment to Africa. During his time at Florida International University, Charles interned at the National Weather Service and the International Hurricane Research Center. Charles worked for the Student Athlete-Academic Center, tutoring FIU athletes in Geoscience and Mathematics. Charles then went on to complete a Master of Science degree in Meteorology from Florida State University. During his time at Florida State University, Charles was a co-author of The role of clouds in the tropospheric NOx cycle: a new modeling approach for cloud chemistry and its global implications, published in Geophysical Research Letters.