CHARACTERIZATION OF THE 2007 SOUTHEASTERN GEORGIA WILDFIRES

by

JEFFREY DARAHYL DENNIS

(Under the Direction of Luke P. Naeher)

ABSTRACT

In April of 2007, wildfires erupted in southeastern Georgia near the municipality of Waycross. Area monitoring of particulate matter ≤ 2.5μm in aerodynamic diameter ($PM_{2.5}$) and carbon monoxide (CO) was conducted in the communities surrounding the fire. The daily exposure levels and wind data were used to approximate exposure to the public. Eight of the 27 sampling locations were above the 35 $\mu g/m^3$ for $PM_{2.5}$ deemed as harmful by the United States Environmental Protection Agency (EPA). No locations exceeded the 9 ppm average for 1-hour and 35 ppm average for 8-hour levels set forth by the EPA for CO. The two factors that have the most influence on exposure were the distance from the fire and duration downwind from the fire. Exposure to the general public was deemed as minimal given the use of public service announcements by local officials and evacuation of areas thought to be receiving large amounts of smoke or in the fires direct path.

INDEX WORDS: $PM_{2.5}$, CO, Community Exposure, Air Pollution, Wildfires, Waycross

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B.S. Chemistry, Columbus State University, 2006

A Thesis Submitted to the Graduate Faculty of The University of Georgia in Partial Fulfillment

of the Requirements for the Degree

MASTER OF SCIENCE

ATHENS, GEORGIA

2008

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August 2008

DEDICATION

I would like to dedicate this thesis to my family-my mother with her perpetual optimism, my brother with his never-ending faith in me, and my father with his encouragement and for making me want to never do wrong in his eyes. Their loving support and sympathetic ear allowed me to finish this work while maintaining my sanity.

ACKNOWLEDGEMENTS

A special thanks belongs to the following people:

- Trina Von Waldner, Rosemarie Parks and the staff of the Southeastern District Health Department, and Jeff Garnett for all their assistance in the field.
- Adam Gray, John Pearce, and Brett Estep for their help in the laboratory and processing of the data.
- Dr. Gary Achtemeier, Scott Goodrick for their help with interpretation of the wind data.
- Dr. Steve Rathbun and Jinae Lee for their help with the statistical analysis.
- Dr. Luke Naeher for his support, guidance, and the opportunities he gave me during my tenure in his lab.
- Ben Hale and Chase Hall for going thru this experience with me as well and all the support and feedback they gave me in the process of writing this thesis.

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CHAPTER 1

INTRODUCTION

Chapter 1 outlines the information presented in each chapter. This chapter is more of a general overview of the paper.

Chapter 2 presents a current literature review of recent wildfires, chemicals in smoke generated from wildfires, and the health effects from wildfire smoke to firefighters and communities impacted by forest fires, all of which are directly relevant to the research presented in this thesis. Different areas of the world where wildfires have recently occurred are examined along with the chemical composition of smoke from various locations. The health effects review is a look into the different adverse effects that have been associated with wildfires and prescribed burns. Firefighters have been a staple of the research and as such many health effects are from studies of firefighters' health.

Chapter 3 contains a manuscript prepared for submission to the Journal of Occupational and Environmental Hygiene. This study describes the air quality experienced during the 2007 Southeastern Georgia wildfires. Real-time levels of particulate matter ≤2.5 microns in aerodynamic diameter ($PM_{2.5}$) and carbon monoxide (CO) from selected locations and corresponding wind data were used to estimate forest fire smoke exposure to the general public and possible trends associated with particulate matter (PM) and CO. The trend witnessed in this research is that $PM_{2.5}$ and CO levels both increase and decrease simultaneously and are strongly correlated with duration downwind from the fire. The data supports that a shift in the wind affects the levels of both $PM_{2.5}$ and CO experienced by an area.

Chapter 4 contains conclusions from the previous chapter and a summary of the work conducted for this research.

CHAPTER 2

SELECTED LITERATURE REVIEW OF HEALTH EFFECTS AND COMMUNITY EXPOSURE FROM WILDFIRES

Introduction

Wildfires are natural processes that are vital for ecosystems and other biota. Wildfires replenish many nutrients to the soil and are useful for forest regeneration. Fire has been viewed as a physical phenomenon and is best illustrated by the fire environment triangle of weather, fuels and topography (Syphard et. al. 2007). Periodic wildfires help to maintain the integrity of many ecosystems, especially those that have strategic adaptation to fire (Syphard et. al. 2007). With the continued expansion of people from urban areas into surrounding rural settings, wildfires become a growing concern to communities in the wildland-urban interface area. The growing number of people in the area close to the wildfires is a concern for adverse effects on the community. The following literature search reviews previous work on community and firefighter exposure to and health effects related to smoke from wildfires, the chemical composition of woodsmoke, and the focus of the research conducted in this thesis.

Health Effects

The 2003 California wildfires were studied for smoke exposure and related adverse community health impact. The fires were to the east of San Diego, CA and affected the metropolitan area. Adverse health effects that were experienced by the citizens of San Diego included asthma, bronchitis, eye irritation, and cardiac arrest (Viswanathan et. al. 2006). Viswanathan and colleagues reported an increase in asthma related hospital visits as well as a slight increase in bronchitis visits to area hospitals. Eye irritation hospital visits were not increased over all of the days of the fire but a slight increase was monitored on days of the greatest ash fallout (Viswanathan et. al. 2006). Medical surveillance of the San Diego County Hospitals showed increases in emergency room visits for asthma for children, eye irritation and higher mortality rates for children (Kunzli et. al 2006). There is also evidence of increased rates of depression and post-traumatic stress disorder from the 2003 California wildfires; this is generally associated with people who had lost something to the fire, such as a home (Marshall et. al. 2007). The increase in these forms of psychosis could be attributed to any loss or disaster.

The potential for adverse health impact from wildfire is an international concern as well. In 1997, forest fires broke out in the 12 provinces of Indonesia and burned for an extended period of times in the tropical forests of the island. In relation to exposures from these Indonesian fires, an increase in upper respiratory tract infections, asthma, and rhinitis were all observed in individuals in Singapore (Emmanuel et. al. 2000). The Indonesian fires also showed increase in respiratory disease, exacerbation of asthma, increased incidence and duration of respiratory disease, declines in lung function and restricted lung activity in populations studied from various areas of Southeast Asia (Frankenberg et. al. 2005). Populations from the provinces of Indonesia also experienced significant increase of bronchial asthma and acute respiratory infection (Aditama et. al. 2000).

Community health impact, in relation to the 2007 wildfires in Eastern Europe/Western Asia, has also been studied. A recent study from Finland showed increased mortality in a population exposed to smoke from the Eastern Europe fires and suggested that this phenomenon was linked to increased particulate matter from these events (Hannien et. al. 2008).

More general studies have been conducted on the health effects from both wood smoke and the air pollution associated with wildfires. Several studies show that particulate matter is a stimulus for precursors to cardiopulmonary disease (Tan et. al. 2000, Sutherland et. al. 2005, Schwartz et. al. 1989). Chronic obstructive pulmonary disease is also suggested to be associated with wildfire smoke (Sutherland et. al. 2005, Osman et. al. 2007), along with increased mortality from significant increases in particulate matter (Vedal et. al. 2006). One study, focusing on wood smoke from wood fire stoves in developing countries, showed an increase in the occurrence of coughing and wheezing in children that lived in the homes (Larson et. al. 1994).

Much more research has been done on wildland firefighters and the effects of chronic and acute exposure to both wildfires and prescribed burns. The leading cause of death among firefighters in the line of duty is sudden cardiac arrest and asphyxiation (CDC MMWR 2006). Decreased lung function between pre- and post-shifts is consistent among studies of wildland firefighters (Slaughter et. al. 2004, Booze et. al. 2004, De Vos et. al. 2006, Betchley et. al. 1997). General symptoms of lower level CO exposure, such as headaches, impaired judgment, and slower reaction times were witnessed in the Betchley et al. (2008) study. Carbon monoxide is a component of smoke because it is a by-product of incomplete combustion and wildfires generally emit high levels of CO. The firefighters also showed increased asthma aggravation and increased mortality in individuals with pre-existing cardiac or respiratory disease (Slaughter et. al. 2004). These symptoms are relevant to community exposure because many of the symptoms exhibited by firefighters are likely also displayed by the general population as well. Given that many firefighters are in top physical condition and they exhibit these symptoms, the general public would likely be more susceptible to smoke and exhibit symptoms similar to these.

The Research into health effects shows adverse effects presented by multiple studies. During the course of this research, only one source refuted these studies. The Cooper et al. study (date???), working with bushfires, shows little or no association between wildfire smoke exposure and health.

Composition of Smoke

The composition of wood smoke varies from location to location. The fuel for the fire is the primary contributor to the composition of the smoke. The smoke can be seen simplistically as partially combusted carbonaceous material, with varying inorganic and organic compounds originating from the fuel for the fire (Leonard et. al. 2007). Smoke is mostly CO_2 and water vapor but the remainder is gas, liquid and solid phase chemicals (Reinhardt et. al. 2004). One constituent which is consistently found in all wood smoke is levoglucosan (Fine et. al. 2002, Lee et. al. 2005). Levoglucosan is a by product of the combustion of the cellulose which makes up the structure of the cell wall of the plants. This fact stands to reason why levoglucosan is found in the smoke from wildfires and prescribed burns. Many other constituents of the smoke are known to be harmful and with synergistic effects being a possibility, the possibility of detrimental effects is high. Two of the products from a forest fire that cause the highest amount of concern are CO and particulate matter. Particulate matter is generally classified into two parts, particulate matter with a diameter of less than 10µm (PM_{10}) and particulate matter with a diameter of less than 2.5µm ($PM_{2.5}$). The $PM_{2.5}$ is of concern because it can permeate deep into the lungs when inhaled and can also have other constituents adhered to the particles, and considering that 74% of the particles emitted from a fire are ≤2.5 µm (Fine et. al. 2002), this causes major concerns. Two of the by-product of particular concern for adhering to $PM_{2.5}$ are formaldehyde and acrolein (Dost et. al. 1991). Both acrolein and formaldehyde are powerful mucosal irritants and as such can cause respiratory tract irritation in sensitive individuals (Dost et. al. 1991). Other constituents of the smoke are all minor additions but still may be cause for concern. Woodsmoke is known to contain at least 5 chemical groups that are known human carcinogens and at least 26 other chemicals listed by the Untied States Environmental Protection Agency as hazardous air pollutants (Naeher et. al. 2007). The volatile and semi-volatile organic compounds (VOC's and SVOC's, respectively) are shown to be released from wildfires. In a study done on the Missoula Valley wildfires in the summer of 2000, significant increases in

SVOC's and slight increase in VOC's were documented (Ward et. al. 2005). Once the fire is no longer blazing, the harm has not abated as the smoldering remains emits VOC's as well as more CO (Lee et al. 2005).

There is evidence to support that the time of year has an impact on the consistency of the smoke (reference?). The two main time frames were consistency of smoke by season are reported are winter and summer. The summer classifications are the most beneficial for comparison to the research from this thesis, as the Waycross smoke exposures reported in this thesis are from late spring. Sulfur dioxide, aluminum oxide, and silicon dioxide were all shown to be at increased levels during summer burns; where as organic carbon, nitrate, and potassium oxide were higher in the winter (Seagrave et. al 2006). Polycyclic aromatic hydrocarbons (PAH's) also displayed this quality of having increased levels of emission in the summer and this is an issue as PAH's undergo metabolic activation and can form DNA adducts that contribute to tumorigenesis (Rothman et. al. 1993). Both mercury (Sigler et. al. 2003) and polychlorinated dibenzodioxins (Ward et. al. 2005) have also been shown to be emitted from wildfires and as such should be taken into consideration when assessing community exposure. Mercury was shown to be emitted from boreal forest fires in Canada and the polychlorinated dibenzodioxins were from New Zealand forests and forests in Australia (need to recite references).

Summary and Conclusions

A considerable level of research has been done investigating adverse health effects associated with wildfires. The majority of the health effects seen are respiratory-related effects such as asthma aggravation, decrease in lung function and cardiopulmonary disease. Only the Cooper and colleagues (year?) study showed no increase in health effects associated with a wildfire. The composition of the smoke from a wildfire is a mix of chemicals, and the primary basis for the makeup of the smoke is the fuel for the fire. All the various chemicals in the smoke could be an area for future research. Real-time $PM_{2.5}$ and CO during wildfire events are not commonly reported in the literature. This thesis aims to contribute to this paucity of data.

The Southeastern Georgia wildfires of 2007 were the focus of the research conducted. The work conducted was area monitoring over several days of several communities surrounding the wildfires. The data from this study were used to estimate smoke exposure to the general public in communities proximate to the fires. This work incorporates $PM_{2.5}$, CO and wind data to estimate public exposure to the fires.

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CHAPTER 3

CHARACTERIZATION OF THE 2007 SOUTHEASTERN GEORGIA WILDFIRES[1]

[1] Jeffrey D. Dennis, Gary Achtemeier, Scott Goodrich, Luke P. Naeher.
In preparation for submission to *Journal of Occupational and Industrial*

ABSTRACT

Wildfires are naturally occurring events that emit large volumes of smoke into the air. With the recent trend in human habitation moving to areas where wildfires happen, exposure to hazardous constituents of the smoke is a growing concern. The research conducted on the 2007 Waycross wildfires looked at ground-level particulate matter ≤ 2.5 microns in aerodynamic diameter ($PM_{2.5}$) and carbon monoxide (CO). The research was conducted using real-time sensors – TSI DustTrak Model 8520 Aerosol Monitor (TSI, Minneapolis, MN, USA) for $PM_{2.5}$, and Langan CO model T15v (Langan Products, Inc., San Francisco, CA USA) for CO. Regional monitoring was conducted and community exposure is estimated. A majority of the elevated levels were seen during the night when much of the community was indoors. Wind direction had an impact on levels of both $PM_{2.5}$ and CO. Eight of the twenty-seven location-day sampling events reported $PM_{2.5}$ levels above the US Environmental Protection Agency 24-hr $PM_{2.5}$ standard of 35 $\mu g/m^3$. No locations exceeded the 9 ppm average for 1-hour and 35 ppm average for 8-hour levels set forth by the EPA for CO. Results of this study demonstrate some occurrences of elevated short-term $PM_{2.5}$ and CO exposures in communities downwind from the 2007 South Georgia wildfires.

INTRODUCTION

Wildfires are naturally occurring incidences, playing a vital role in some ecosystems, but in some situations have considerable adverse effects on humans and their lifestyle. In relation to community exposure to wildfires, Slaughter and colleagues (2004) report that asthma events are increased, as well as increased mortality for individuals with pre-existing cardiac or respiratory disease (Slaughter et al. 2004). Wildfire smoke has also been shown to contain many harmful chemicals and the composition varies with the composition of the fuels (Naeher et al. 2007, Robinson et al. 2004, Sillanpää et al. 2005), so naming one harmful constituent is difficult. One constituent of concern is particulate matter (PM) not only because of its adverse effect on respiratory function (Sutherland et al. 2005), but because it also carries other harmful agents (Naeher et al. 2007).

Several studies have been conducted on health effects in populations from communities exposed to smoke from wildfires. During the California wildfires of 2003, research was conducted on the health effects experienced by communities surrounding San Diego. Increased hospital visits were seen for asthma, bronchitis, eye irritation and cardiac arrest (Viswanathan et al. 2006). There were also noted increases in post traumatic stress disorder and depression, however this more strongly associated with people who had lost something to the fire (Marshall et al. 2007). The 1997 forest fires of Indonesia had similar studies conducted on health effects in Singapore (Emmanuel et al. 2000) as well as the rest of Southeast Asia (Frankenberg et al. 2005, Aditama et al. 2000) with similar effects reported. A more recent study in Finland on the effects of wildfires in Eastern Europe showed increased mortality from increased PM (Hannien et al. 2008).

Wildfire can continue for extended periods of time, and this duration of wildfires is an important factor in potential community health impact from wildfires. Prolonged wildfires in areas where wildfires are not a common occurrence are where the greatest detrimental effect is noticed. After the fire is no longer blazing, the harm is not abated as the smoldering remains emit more CO and volatile organic compounds (Lee et al. 2005).

The objectives of this research are to report smoke monitoring in communities proximate to the 2007 southeastern Georgia wildfires during the early stages of these fires, and to use these data along with wind speed and direction data to estimate community exposure to wildfire smoke during these events.

METHODS

On April 18th, state officials contacted Luke Naeher at the The University of Georgia (UGA) and requested assistance with smoke monitoring in the areas impacted by the ongoing southeast GA wildfires. On April 21, 2007 a monitoring crew from Dr. Naeher's lab arrived in Waycross, GA, and started monitoring smoke in areas local health officials from the Southeastern District Health Department (SDHD) and the Ware County School District (WCSD) believed were at risk from smoke from the fires. The monitoring included real-time $PM_{2.5}$ and CO measures collected at select locations around the seven counties of the southeastern district.

Sampling timeframe and location

The monitoring was done over from April 21st to April 25th 2007. The locations to be sampled each day were decided based on potential for community exposure and weather forecasts for the following day (i.e., likelihood of smoke at populated locations), accessibility for the sampling team, and the data needs of the SDHD and the WCSD. Two sampling locations that were monitored throughout the study were the Waycross Police Department for its centralized location in the town, and the Douglas, GA sampling location. Other outdoor sampling locations were: Argyle, Georgia at a half-way house; the health department in Charlton County; the Clinch County Hospital; the Georgia Forestry Commission at the Okefenokee Swamp; Ware County High School; the Pierce County Resource Center; and the Ware County Sheriff's Office. The sampling locations on each day of the study are presented in Figure 3-1. In addition to the outdoor sampling sites, two indoor locations were also selected for monitoring – the Manor Magnet School, and the Ruskin Elementary School (see Figure 3-1). Both of these sites were selected for sampling because the schools had been "smoked out" in some part of the week preceding the sampling. Following these "smoke outs", the local school board took action to remove the smoke smell and any residual smoke in these locations. The monitoring at these sites was done to help SDHD and WCSD officials estimate the efficiency of these actions to remove smoke smell and residual smoke, and to provide these officials with data to help them decide when to re-open the schools.

Sampling equipment

Real-time $PM_{2.5}$ and CO were sampled at each location. $PM_{2.5}$ was measured in 30-s intervals with TSI DustTrak Model 8520 Aerosol Monitors (range 0.01 mg/m^3 to 100 mg/m^3; resolution 0.01 mg/m^3) with dataloggers (TSI, Minneapolis, MN, USA) (DustTrak),. CO was measured in 30-s intervals with Langan CO model T15v sensors (range 0-2000 ppm; resolution 1 ppm) with dataloggers (Langan Products, Inc., San Francisco, CA USA) (Langan). These instruments were calibrated before the study at the Air Quality Lab at UGA and the DustTrak monitors were zero calibrated in the field each day.

The setup at each sampling location consisted of the DustTrak being placed in a secure location and the inlet tubing placed at normal breathing height (approximately 1.5 m). The Langan monitors were placed at the same height and within 1 m of the DustTrak inlet tubing.

Sampling duration

The sampling duration varied from day to day due to the various locations sampled and the varying time to pickup and set-up each apparatus at each old and new location, respectively (see Table 3-1). All locations were allowed to sample overnight, and into the morning of the next day. The aim was to get a 20 hr sample. At the end of each sampling period, the monitors were downloaded and reset for the next sampling location.

DustTrak normalization/data adjustment methods

DustTraks have minor variation between each machine. In order to compare DustTrak data collected from several machines over the same time frame, the units need to be tested in the PM environment of the study in question, and normalization factors need to be developed so that all of the instruments can be benchmarked to one instrument. In the current study, this was done to determine a normalization ratio for each DustTrak used in this study. Toward this end, all six DustTraks used in this study were sampled co-located temporally and spatially in Fargo, GA, which was selected because it was experiencing heavy smoke during this sampling day. The sampling method was the same as at all of the previous sampling location with respect to the DustTrak and Langan monitors.

The process of normalizing each DustTrak to each other was achieved taking the average exposure levels for each DustTrak over the sampling period and compared to each measurement. The median DustTrak measurement of the group was chosen as the bench measurement for that run and a normalization factor was obtained for each DustTrak by dividing the bench DustTrak measurement by the raw DustTrak measurements for each individual DustTrak. The normalization factor for each DustTrak was then multiplied into the raw DustTrak data to allow for a near uniform reading for the DustTrak machines (see Table 3-1 and Figure 3-7).

In conjunction with all of the co-located DustTrak monitors, two BGI PQ200 Ambient Fine Particulate Samplers (PQ200), operating at a flow rate of 16.7 L/min, were setup to sample time-integrated $PM_{2.5}$ data that were co-located temporally and spatially with the DustTrak $PM_{2.5}$ data. The PQ200 is a US EPA Federal Reference Method for $PM_{2.5}$. The PQ200 data were collected so that the DustTrak $PM_{2.5}$ data could be adjusted down to actual $PM_{2.5}$ levels, based on an equation derived from the co-located DustTrak $PM_{2.5}$ data and the PQ200 $PM_{2.5}$ data.

The process of reducing the DustTrak data to give a more accurate reading was done by taking the data collected from the PQ200 and using that measurement to determine a factor by which each DustTrak machine to be reduced by (see table 3-1). The DustTrak measurement used to determine the reduction factor was the bench DustTrak measurement for the Fargo location as this as was used for the normalization factor. The reduction ratio was determined by dividing the bench DustTrak measurement by the gravimetric average measurement. The reduction ratio was then taken and applied to the normalized data by dividing each data point by the reduction factor. This process gives the finalized data that is presented herein.

Gravimetric analysis:

Filters were stored under controlled climate conditions (20.6 ± 1.4^{o}C) for at least 48 hours prior to pre- and post-weighing. Filters were weighed twice using the Cahn C-35 microbalance with a sensitivity of ± 1 μg following the EPA's Quality Assurance Guidance Document. The mean net mass of the field blanks was subtracted from the net mass of the sample filters. However, due to the minimal change in the field blank masses, this had little effect on the $PM_{2.5}$ mass concentrations. According to the previous literatures (Koistinen et al. 1999, Yanosky et al. 2002), air densities during weighing sessions, nominal densities of calibration masses, and a filter density were used to adjust the balance readings for the buoyancy effect of air.

Wind Data

The wind direction data used in the analyses for this study are from the National Weather Service (http://srh.noaa.gov/data/obhistory/KAYS.html) for the Waycross/Ware County area. There is a small gap in the wind direction data collected from April 22nd at 17:00 till 21:00 hours.

Statistical Analysis

For each of the data sets obtained, descriptive statistical analysis was run including means and 95% confidence intervals. Data from both instruments were collected in 30 second intervals, and so showed erratic behavior over time with a number of outlying observations. To reduce this noise, the data were smoothed over time using LOESS regression (Cleveland et al. 1988). LOESS regression predicts the concentration at each point in time by fitting a simple linear regression model using only observations in the neighborhood of that point in time, the width of that neighborhood determined by the band width. Weighted least squares estimated are used to fit the regression models, with weights determined by a kernel function. Kernel smoothing was done in SAS 9.1 using the LOESS program. The LOESS procedure was first run on all the data sets to obtain an optimal smoothing parameter for each data set. After obtaining the optimal parameter for each data set, the range of the parameters was analyzed and a bandwidth of 10.8 minutes was chosen for use on all the data sets for uniformity across all data sets. For each sampling interval, the area under the smoothed curve was computed to obtain an estimate of the total exposure during that interval, from which exposure to the community can be assessed. The area under the curve analysis for each location can be seen in Table 3-2.

For the correlation of distance, duration and concentrations, a Spearman's rank correlation was performed in SAS 9.1. Spearman's rank correlation coefficient or Spearman's rho, often denoted by the Greek letter ρ (rho) or as r_s, is a non-parametric measure of correlation. It assesses how well an arbitrary monotonic function could describe the relationship between two variables, without making any assumptions about the frequency distribution of the variables.

RESULTS

Table 3.2 presents the averages for both $PM_{2.5}$ and CO at each sampling location for each sampling day. The data includes the averages over the sample duration, the 95% confidence interval, and the area under the curve analysis data for the $PM_{2.5}$ data. Table 3-3 presents the distance that each sample location was downwind from the fire, as well as the duration of the sampling in the wind path. The process for making this analysis was determining the direction vector on a 360° circular scale that the sampling location was from the fire (+/- 20°) and cross-referencing this with the wind data collected. The wind data collected was in 20 minute intervals so the time downwind is also in 20 minute intervals. The Ruskin Elementary School sample location was located in the actual burn area so no directional vector could be determined. As such, for the Ruskin sample no duration is determined. Duration in wind path for the Fargo location is also not presented as these data were collected solely for adjusting the DustTrak data.

Table 3.4 presents the Spearman correlation for $PM_{2.5}$, duration downwind from the fire, and distance from the fire. The data show a strong correlation between $PM_{2.5}$ and duration the sampling location is downwind from the fire ($R = 0.805$). The correlation between distance from the fire to sampling location and $PM_{2.5}$ was weaker and negative ($R = -0.512$). Similarly, Table 3.5 presents the Spearman correlation between CO, duration downwind from the fire, and distance from the fire. CO and both duration down wind ($R = .367$) and distance from the fire ($R = -0.177$) were not highly correlated.

Figures 3-2 to 3-7 show all $PM_{2.5}$, CO, and wind speed and direction data for each location sampled on each sampling day. The top panel in each figure reports $PM_{2.5}$, the middle panel CO, and the bottom panel wind speed and direction.

The data from Table 3.1 and Figure 3-2 show that the exposure of the community surrounding the fire was minimal on April 21st. The three locations that showed exposure levels above the US EPA 24-hr $PM_{2.5}$ National Ambient Air Quality Standard of 35 μg/m^3 for $PM_{2.5}$ were the Manor Magnet School and Ruskin Elementary School, both of which were sampled indoors, and the outdoor ambient sample at the half-way house facility at Argyle. The Manor Magnet School (238.4 μg/m^3) was used for a town meeting earlier that day. The source for the influx of smoke was the opening of the doors of the school during this time and the nocturnal inversion which took place during the night. Ruskin Elementary School (209.3 μg/m^3) can also be attributed to the nocturnal inversion. During this sampling period, the Ruskin Elementary School was closed to the public and the surrounding community was evacuated from the area, therefore minimal exposure to the general public can be inferred. The Argyle location saw slightly elevated levels (49.7 μg/m^3) with a majority of the exposure time being during the time frames of approximately 17:00 hours to 18:00 hours and 06:00 hours to 8:00 hours (Figure 3-2). These time frames coincide with when employees and residents of the facility were traveling to and from work. The sampling location chosen at the facility was near the gravel road leading to the facility for the security of the sampling equipment. The proximity to the gravel road as well as car exhaust from traffic on this road may have slightly contributed to the elevated $PM_{2.5}$ observed at this location. The Clinch County Hospital location also experienced slightly elevated readings (31.6 μg/m^3) during the commute time frame. The sampling location at this site was also in a secure location, which was close to the place where the employees and ambulances came into the hospital. The road was paved so the readings were not as high as the Argyle location. All other sampling locations on this day were well beneath 35 μg/m^3. Regarding CO, no sampling location showed levels above 9 ppm for an 8-hr average or 35 ppm for a 1-hr average. This day's data shows a strong trend with the wind direction (Figure 3-2), as well as nocturnal inversion-related overnight/early morning increasing $PM_{2.5}$ and CO at most of the sampling sites.

Table 3.2 and Figure 3-3 contain the data from April 22nd. None of the sampling locations reported $PM_{2.5}$ exceeding 35 $\mu g/m^3$. The wind was blowing primarily from the Southeast this day and short-term elevated levels were monitored at the locations in the winds path. The early morning spike at the Waycross Police Station could not be accounted for as the nocturnal inversion had already lifted and there was no wind at the time. The CO for this day tracked the increasing and decreasing with $PM_{2.5}$ and wind direction (Figure 3-3). The Waycross Police Station data has some noise in it and can be attributed to police vehicles entering and leaving the station. None of the CO levels were above 9 ppm for an 8-hr average or 35 ppm for a 1-hr average.

Table 3.2 and Figure 3-4 contain the data for April 23rd. The wind throughout the day was variable going between the ranges of Southwest to Southeast. The sampling locations experienced little smoke throughout the day, however at night a nocturnal inversion was evident. The inversion is evident at the Pierce County Resource Center, Charlton County Health Department, and the Clinch County Hospital. The only location with $PM_{2.5}$ levels above 35 $\mu g/m^3$ was the Waycross Police Station (42.8 $\mu g/m^3$). The Douglas, Ga. location was borderline (32.9 $\mu g/m^3$) and the majority of the exposure was from the nocturnal inversion the previous day that was caught at the beginning of the sampling period. Community exposure was minimal because the majority of the exposure happened during the middle of the night when most people indoors. The CO continued to follow the trend of increasing/decreasing with increasing/decreasing $PM_{2.5}$ (Figure 3-4). No site had CO levels above 9 ppm for an 8-hr average or 35 ppm for a 1-hr average. There was some noise at the Pierce County Resource Center at the end of the sampling period that no explanation could be deduced.

Table 3.2 and Figure 3-5 contain the data collected on April 24th. The wind was primarily from the South and Southwest for the majority of the sampling period. The Pierce County Resource Center showed extended periods of elevated $PM_{2.5}$ levels, however no wind was blowing in the direction of the sampling location and time frame is not consistent with a nocturnal inversion. The $PM_{2.5}$ exposure at the Pierce County Resource Center (101.0 $\mu g/m^3$) was above the 35 $\mu g/m^3$ level. The Ware County High School (48.6 $\mu g/m^3$) and the Waycross Police Station (34.1 $\mu g/m^3$) were directly in the wind's path and elevated $PM_{2.5}$ levels can be seen for extended periods of time. The trend of CO following $PM_{2.5}$ levels continued for this day (Figure 3-5). The Douglas, GA and the Charlton County Health Department did not follow this trend due to the low levels of smoke exposure at these locations. The highest CO concentrations observed at any location were well below 9 ppm for an 8-hr average or 35 ppm for a 1-hr average.

Table 3.2 and Figure 3-6 contain the data collected on April 25th. On this day of sampling, the fire entered the Okefenokee Swamp and began emitting massive amounts of smoke. The Georgia Forestry Commission was located within 2 miles of the fire and received heavy smoke this day. The $PM_{2.5}$ level experienced at the Georgia Forestry Commission (314.9 $\mu g/m^3$) was the highest levels experienced during the study. The area surrounding the Georgia Forestry Commission had been evacuated so the majority of people who were in the area were firefighters and other emergency workers. There was a time period were levels as high as 3000 $\mu g/m^3$ were monitored. The firefighters and emergency workers exposures were unavoidable with the duties of fighting the fire. The Waycross Police Department and the Charlton County

Health Department also show slightly elevated levels of $PM_{2.5}$ on this day, most likely due to change in the wind direction. The Pierce County Resource Center had a level of 43.2 $\mu g/m^3$. The trend of CO following $PM_{2.5}$ continued on this day with the Douglas, GA and Charlton County Health Department sampling sites not showing the trend (Figure 3-6). Again, this is most likely due to the low levels experienced at both these locations. The best sampling location to see these trends at was the Georgia Forestry Commission where the trend is clearly evident. No sampling location reported CO over 9 ppm for an 8-hr average or 35 ppm for a 1-hr average.

Table 3.1 and Figure 3-7 report the co-located $PM_{2.5}$ and CO data collected at the Fargo location on May 10th. This includes the averages of the DustTraks from the Fargo sampling location, the PQ200 gravimetric data, along with the normalization proportion and reduction ratio.

DISCUSSION

The levels of $PM_{2.5}$ observed at the multiple Waycross locations showed elevated levels throughout the entire length of the study. These levels were generally associated with a shift in the wind direction. Eight of the 27 location/day results listed in the results section (excluding the May 10th data used for normalization and reduction) had full sample duration $PM_{2.5}$ levels above 35 $\mu g/m^3$. The highest levels were experienced at the locations that had the general public evacuated or were during the middle of the night when most people were indoors. None of the location/day results for CO exceed the EPA standards of 9 ppm for an 8-hr average or 35 ppm for a 1-hr average..

Previous studies of community exposure and effects from wildfire smoke have shown that prolonged elevated smoke exposures can affect the welfare of the general public (Viswanathan et al. 2006, Emmanuel et al. 2000, Aditama et al. 2000). In the present study, the

SDHD's release of public service announcements and canceling of public functions minimized exposure to the general public.

There were a number of limitations in this study. One limitation was the sample location selection process. The initial location selection process was limited in that the sampling locations selected were sites that were smoky the previous day, but not necessarily smoky on the subsequent day when we were sampling. This was in part remedied by making a semi-circle on the north side of the fire on the second day of sampling and instead of sampling "hot spots" from the previous day, sampling locations were chosen due to their location relative to the fire and projected wind for the next day. Another limitation was the lack of direct comparability between multiple DustTrak units and the fact that DustTraks over-report $PM_{2.5}$. These issues were remedied by the normalization and reduction samples that were done with data collected at the Fargo location. The lack of directly comparable study region controls is another limitation to this study. The Douglas, GA location was initially sited with the intent that it would serve as a low to no smoke control site. However, like much of the state of Georgia, the Douglas, GA location on occasion was inundated with smoke from the wildfires. Additional control data used in our analyses were the ambient $PM_{2.5}$ data from the region from the Georgia Environmental Protection Division (EPD), which report annual ambient $PM_{2.5}$ levels of 13.0 $\mu g/m^3$ and 14.5 $\mu g/m^3$ for southeastern Georgia for 2005 and 2006, respectively. All of these limitations must be considered when reviewing and interpreting the data presented in this study.

After review of both CO data and the $PM_{2.5}$ data, the areas that receive harmful concentrations vary day to day and are influenced by a two factors. The biggest factor in determining levels of high exposure is location. The closer to the fire, the higher the exposure. This is the easiest factor to overcome as the general public was always a considerable distance from the fire. The next factor to determining higher levels of exposure is wind direction. With the wind shifting at any time, new area may newly be exposed to elevated smoke levels. The best way to control for this is to issue public advisories and hope that the public listens. In the fires under investigation in this study, public advisories were issued from the SDHD. However, anecdotal evidence suggests that many individuals in the impacted region were reluctant to comply with warnings to stay indoors unless smoke was actually visible in the area.

CONCLUSION

The $PM_{2.5}$ data shows that there was increased $PM_{2.5}$ throughout the entire monitoring period, with episodes of elevated exposure in select regions on select days. The CO results track closely in time with the $PM_{2.5}$ results, although the CO levels generally did not elevate to levels of health concern. $PM_{2.5}$ levels were strongly correlated with how long the sampler was downwind of the fire, while the correlation between $PM_{2.5}$ levels and distance from the fire was negative, and not as strong.

ACKNOWLEDGEMENTS

The firefighters and other emergency workers had the greatest $PM_{2.5}$ and CO exposures and deserve thanks for all their hard work containing the fire. The researchers also give thanks to Dr. Rosemarie Parks, the staff of the SDHD, Kevin Caspary at the State EPD, Jeff Garnett and Adam Gray for their help with the field work and data analysis, and Jinae Lee for help with the statistical analysis.

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Table 3.1. Dustrac real-time and PQ200 gravimetric time-integrated results and comparison from Fargo, GA study

Fargo Dustrak results comparison for development of normalization factors for intra-unit comparison

DustTrak serial number	$PM_{2.5}$ (ug/m^3)	Normalization proportion
*85201221	364.9	Bench = 1.0
23094	312.9	1.166
23092	388.7	0.939
24068	298.0	1.224
23093	396.6	0.920
85201218	363.3	1.004

* This Dustrak sampler's results were in the middle range of all the Dustrak data, so this value is the bench mark that the other Dustrak values are adjusted to.

Fargo Gravimetric Data

Average Filter Preweight in mg	$PM_{2.5}$ (ug/m^3)
170.700	99.1
173.459	101.5
Average	100.3
Real-time to gravimetric reduction ratio	3.64

Table 3.2. $PM_{2.5}$ and CO by sampling date and location

Location	Date	Duration	PM and CO (+/- 95% CI) $PM_{2.5}$ ($\mu g/m^3$)	CO (ppm)	PM Area Under The Curve Analysis
Argyle, GA					
	4/21/2007	18:58:00	49.7 (+/- 2.73)	1.1 (+/- 0.02)	56260.3
Charlto County Health Department					
	4/23/2007	30:00:00	3.8 (+/- 0.04)	0.4 (+/-0.007)	6892.9
	4/24/2007	20:57:00	5.5 (+/-0.04)	0.4 (+/-0.007)	6932.7
	4/25/2007	22:18:00	7.1 (+/-0.06)	0.3 (+/-0.006)	9548.7
Clinch County Hospital					
	4/21/2007	18:21:30	31.6(+/- 1.6)	0.9 (+/-0.01)	34763.1
	4/23/2007	15:10:00	3.6(+/-0.07)	1.5 (+/- 0.08)	3268.0
	4/25/2007	23:49:30	5 (+/-0.06)	1.4 (+/-0.01)	7124.2
Douglas, GA					
	4/21/2007	15:48:30	6.9 (+/-0.1)	1.9 (+/-0.02)	6502.2
	4/22/2007	16:19:30	11.7 (+/-1.0)	2.2 (+/-0.04)	11410.9
	4/23/2007	23:21:00	32.9 (+/-2.9)	1.6 (+/-0.03)	45981.0
	4/24/2007	23:55:30	4.2 (+/-0.03)	1.4 (+/-0.009)	5953.5
	4/25/2007	24:22:30	4. 2(+/-0.03)	1.3 (+/-0.009)	6143.2
Fargo					
DT6	5/10/2007	18:40:00	100.3 (+/- 0.002)	2.2 (+/-0.03)	108632.5
DT5	5/10/2007	18:40:00	100.3 (+/- 0.002)	2 (+/-0.03)	108782.5
DT4	5/10/2007	18:40:00	104.9 (+/- 0.002)	1.2 (+/-0.02)	109345.5
DT3	5/10/2007	18:40:00	104.9 (+/- 0.002)		109215.7
DT2	5/10/2007	18:40:00	104.9 (+/- 0.002)		109682.6
DT1	5/10/2007	18:40:00	104.9 (+/- 0.002)		109591.8
Georgia Forestry Commision					
	4/22/2007	19:56:30	7.4 (+/-0.4)	0.8 (+/-0.009)	8314.8
	4/25/2007	22:10:00	314.9 (+/-14.9)	3.2 (+/-0.1)	416197.9
Manor Magnet School					
	4/21/2007	19:34:00	238.4 (+/-7.4)	3.5 (+/-0.08)	278879.0
Pierce County Resource Center					
	4/23/2007	24:18:00	16.2 (+/-0.9)	0.8 (+/-0.02)	23628.6
	4/24/2007	17:56:30	101 (+/-6.4)	1.2 (+/-0.03)	108632.5
	4/25/2007	14:46:00	43.2 (+/-2.6)	1.2 (+/-0.04)	38151.9
Ruskin Elementary School					
	4/21/2007	20:07:30	209.3 (+/-9.1)	6.5 (+/-0.02)	252405.6
Ware County High School					
	4/23/2007	30:04:30	32.4 (+/-2.1)	1.6 (+/-0.03)	6892.9
	4/24/2007	18:12:30	48.6 (+/-2.5)	1.5 (+/-0.02)	53083.5
Ware County Sheriff's Office					
	4/22/2007	17:51:00	3. (+/-0.1)	1.4 (+/-0.02)	4001.9
Waycross Police Department					
	4/21/2007	21:31:00	6.5 (+/-0.06)	1.8 (+/-0.01)	8423.8
	4/22/2007	25:38:30	6 (+/-0.3)	1.4 (+/-0.02)	9242.6
	4/23/2007	17:17:30	42.8 (+/-3.6)	1.8 (+/-0.04)	44356.3
	4/24/2007	24:51:00	34.1 (+/-2.1)	1.3 (+/-0.02)	50855.1
	4/25/2007	22:16:30	13.5 (+/-0.5)	1.3 (+/-0.02)	17976.8

Table 3.3. Sampling location distance from fire and duration of sampling location in wind path

Location	Date	Distance from fire (miles)	Duration (minutes)
Argyle, GA			
	4/21/2007	8	340
Charlton County Health Department			
	4/23/2007	30	20
	4/24/2007	30	40
	4/25/2007	30	20
Clinch County Hospital			
	4/21/2007	18	300
	4/23/2007	30	60
	4/25/2007	30	0
Douglas, GA			
	4/21/2007	32	420
	4/22/2007	40	260
	4/23/2007	45	520
	4/24/2007	45	160
	4/25/2007	40	40
Georgia Forestry Commision			
	4/22/2007	5	0
	4/25/2007	0.25	420
Manor Magnet School			
	4/21/2007	6	340
Pierce County Resource Center			
	4/23/2007	16	200
	4/24/2007	16	760
	4/25/2007	16	560
Ruskin Elementary School			
	4/21/2007	0	in fire area
Ware County High School			
	4/23/2007	18	220
	4/24/2007	18	320
Ware County Sheriff's Office			
	4/22/2007	8	160
Waycross Police Department			
	4/21/2007	6	0
	4/22/2007	5	160
	4/23/2007	8	320
	4/24/2007	8	460
	4/25/2007	8	300

Table 3.4. Correlation of distance from fire, duration downwind and $PM_{2.5}$ concentration

The CORR Procedure
3 Variables: distance duration PMconc

Simple Statistics

Variable	N	Mean	Std Dev	Median	Minimum	Maximum
distance	26	19.7	14.0	17.0	0.0	45.0
duration	26	274.6	216.3	280.0	0.0	760.0
PMconc	26	49.1	80.3	14.9	3.6	314.9

Spearman Correlation Coefficients, N = 26
Prob > |r| under H0: Rho=0

	distance	duration	PMconc
distance	1	-0.300	-0.512
		0.137	0.008
duration		1	0.805
			<.0001
PMconc			1

Table 3.5. Correlation of distance from fire, duration downwind and CO concentration

The CORR Procedure
3 Variables: distance duration COconc

Simple Statistics

Variable	N	Mean	Std Dev	Median	Minimum	Maximum
distance	27	19.1	14.0	16.0	0.0	45.0
duration	27	264.4	218.6	260.0	0.0	760.0
COconc	27	1.6	1.2	1.4	0.3	6.5

Spearman Correlation Coefficients, N = 27
Prob > |r| under H0: Rho=0

	distance	duration	COconc
distance	1	-0.196	-0.177
		0.328	0.376
duration		1	0.367
			0.060
COconc			1

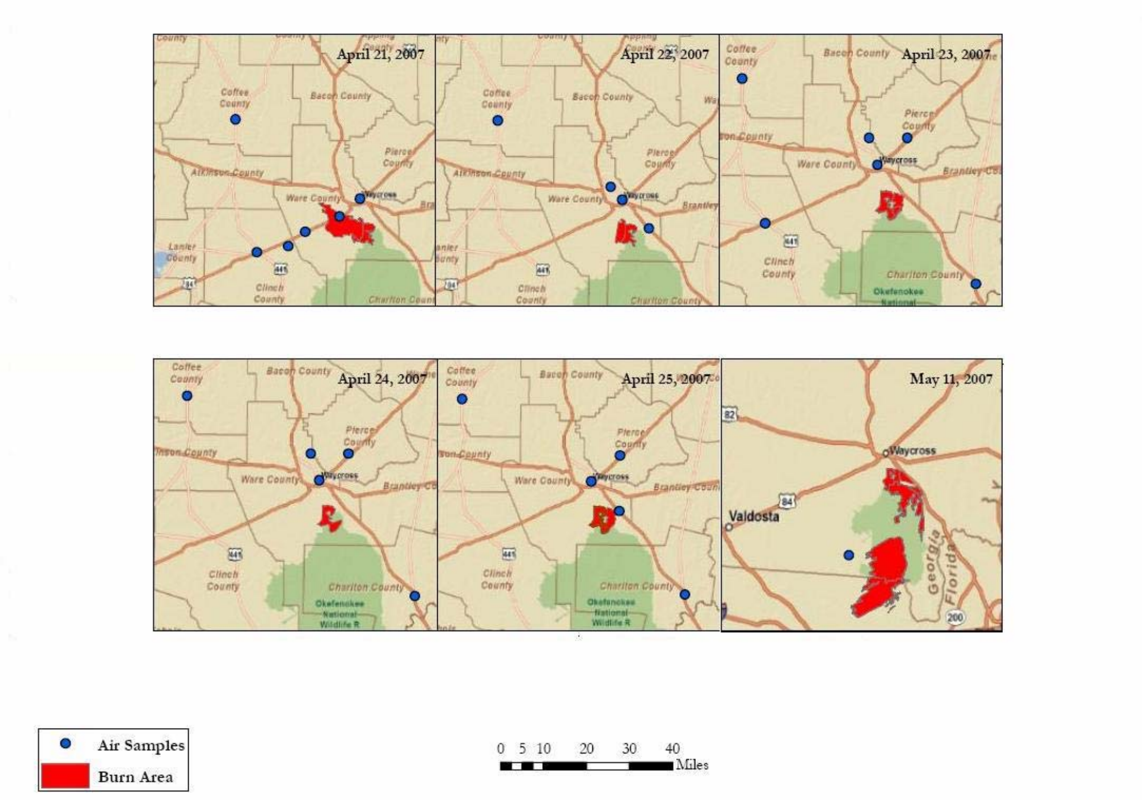
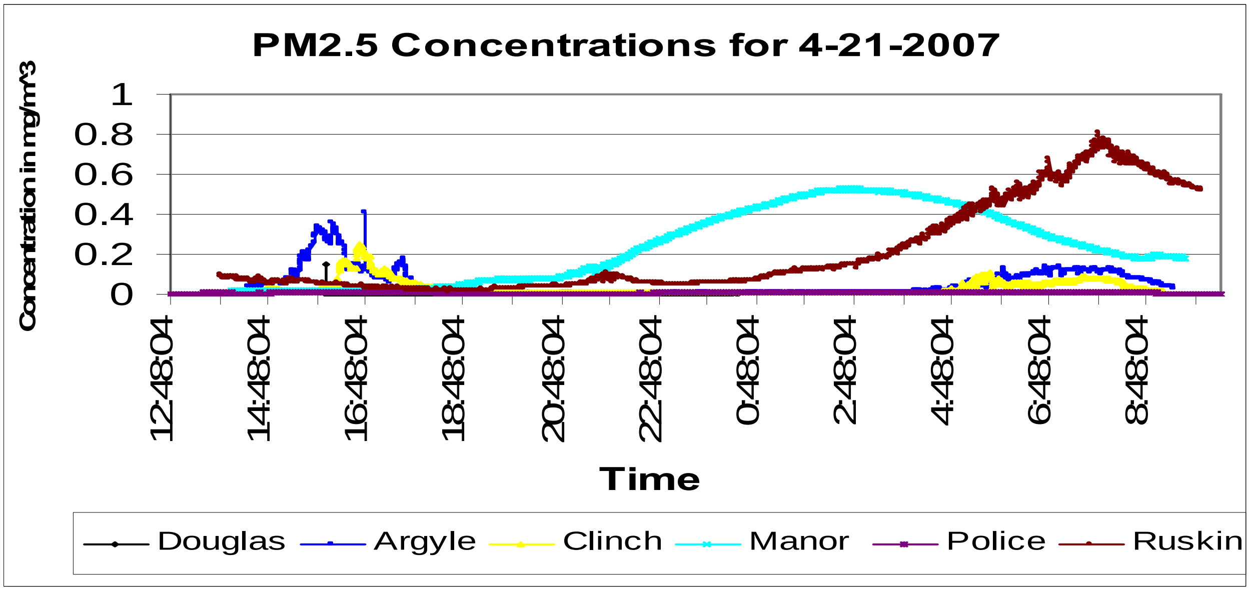
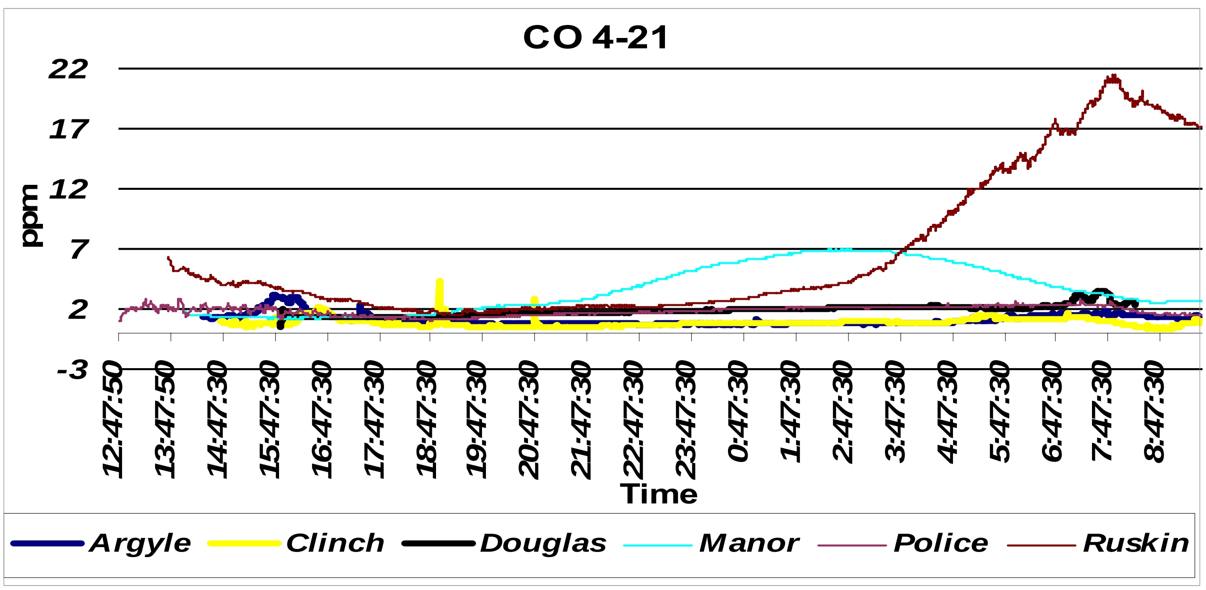


Figure 3-1 Map of sampling locations by day of the 2007 Waycross wildfires





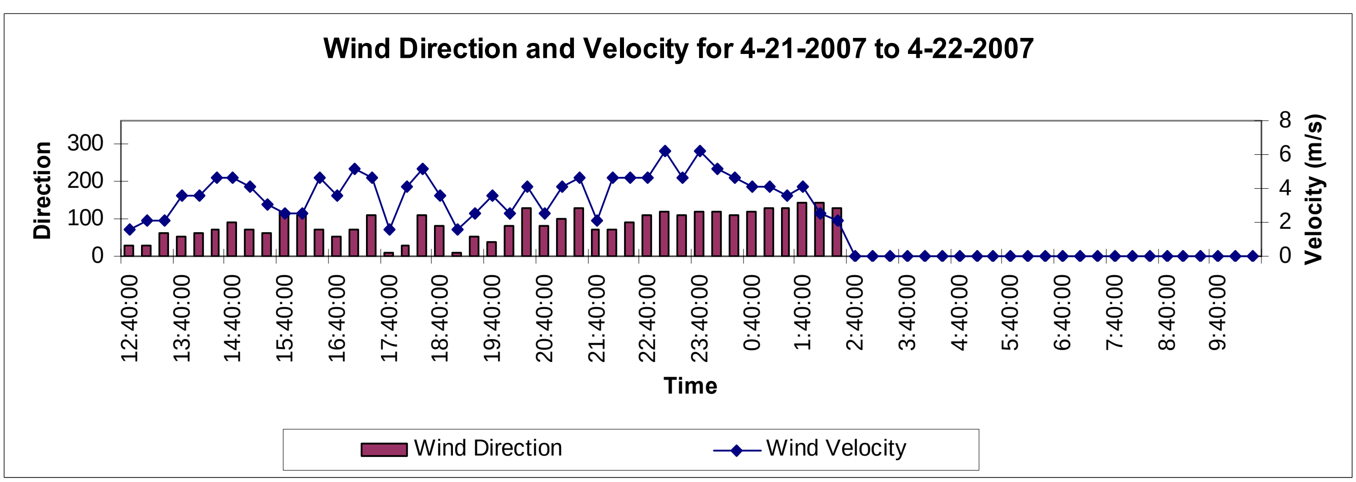


Figure 3-2: $PM_{2.5}$, CO, and wind data for April 21, 2007

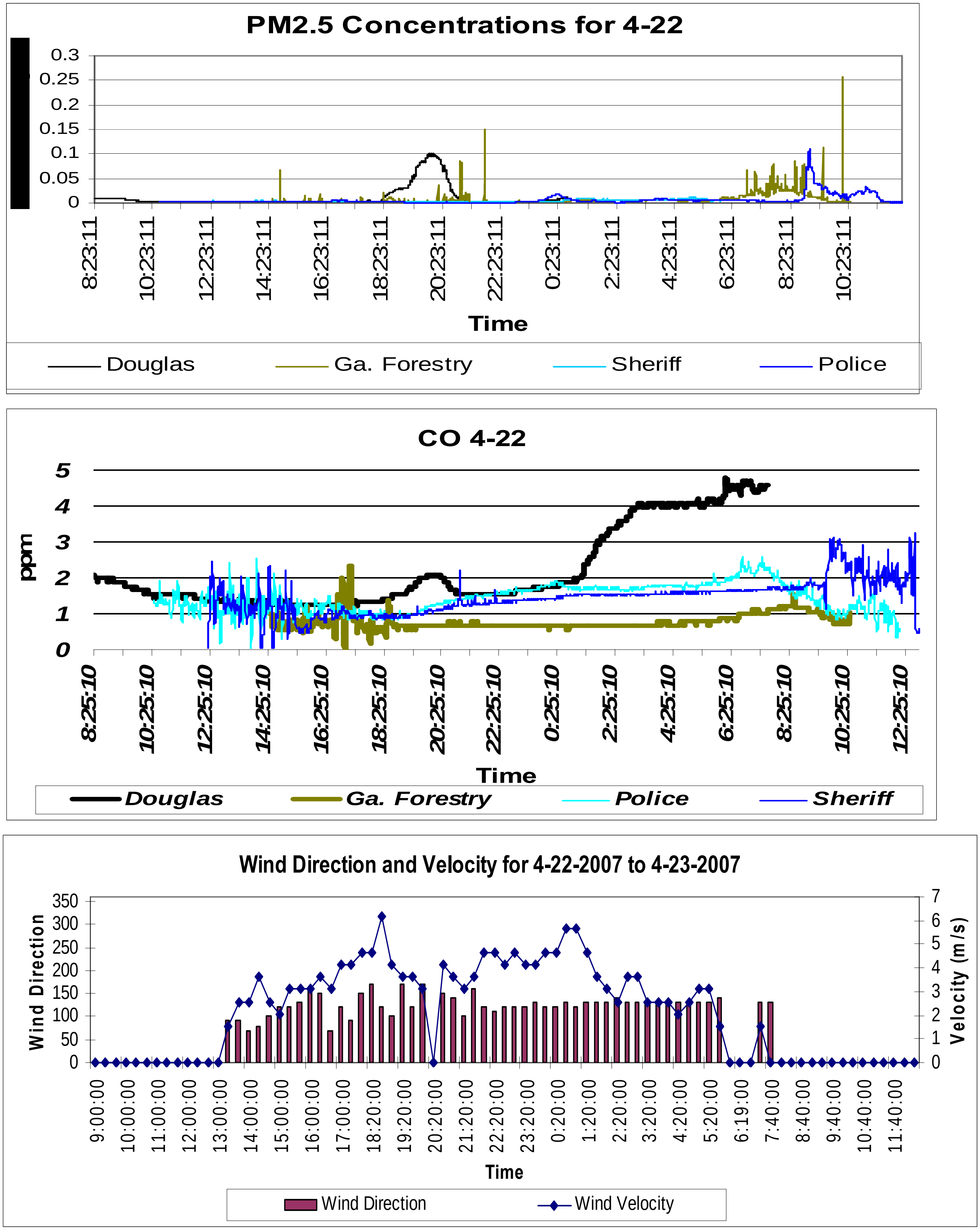


Figure 3-3: $PM_{2.5}$, CO, and wind data for April 22, 2007

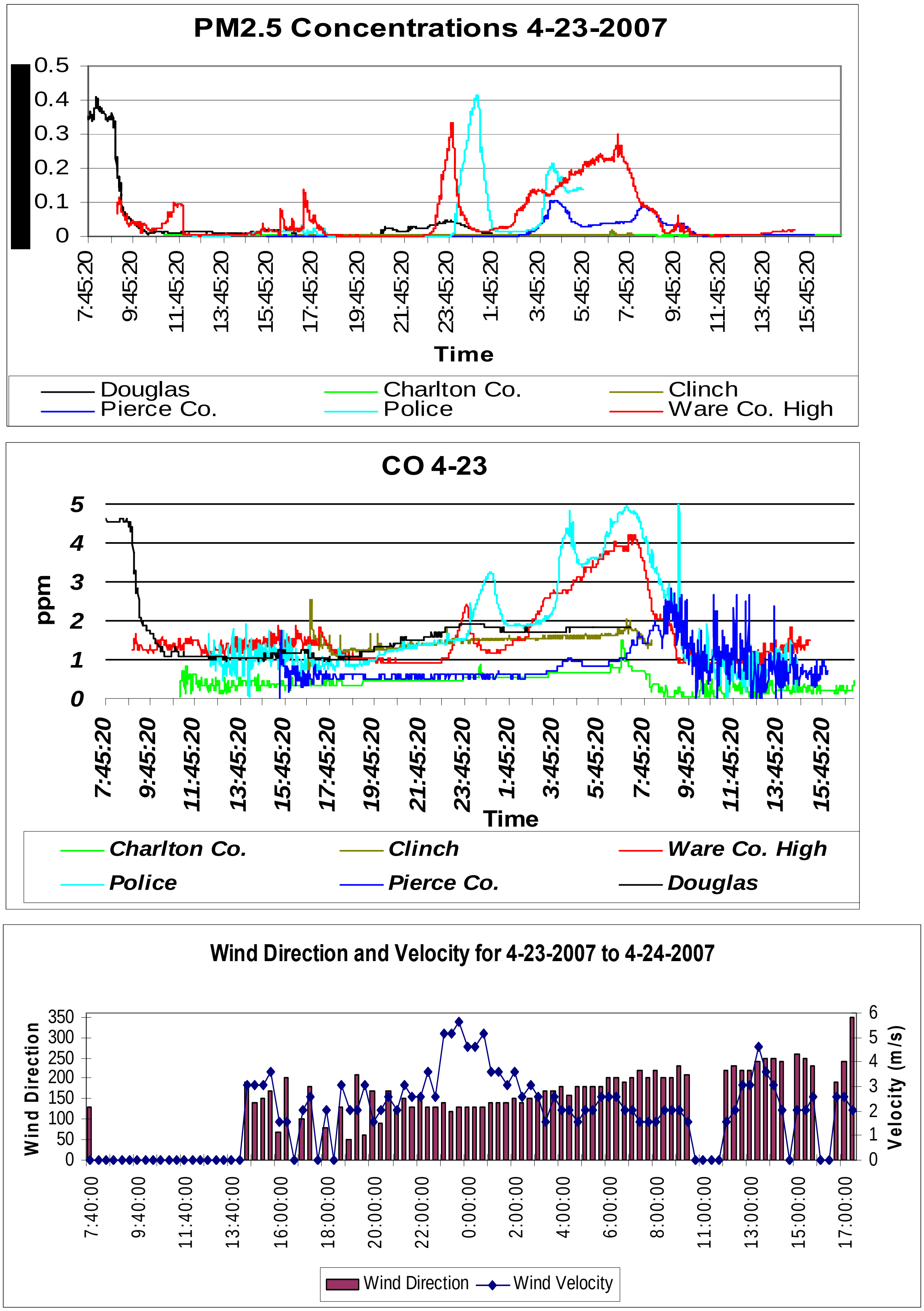


Figure 3-4: $PM_{2.5}$, CO, and wind data for April 23, 2007

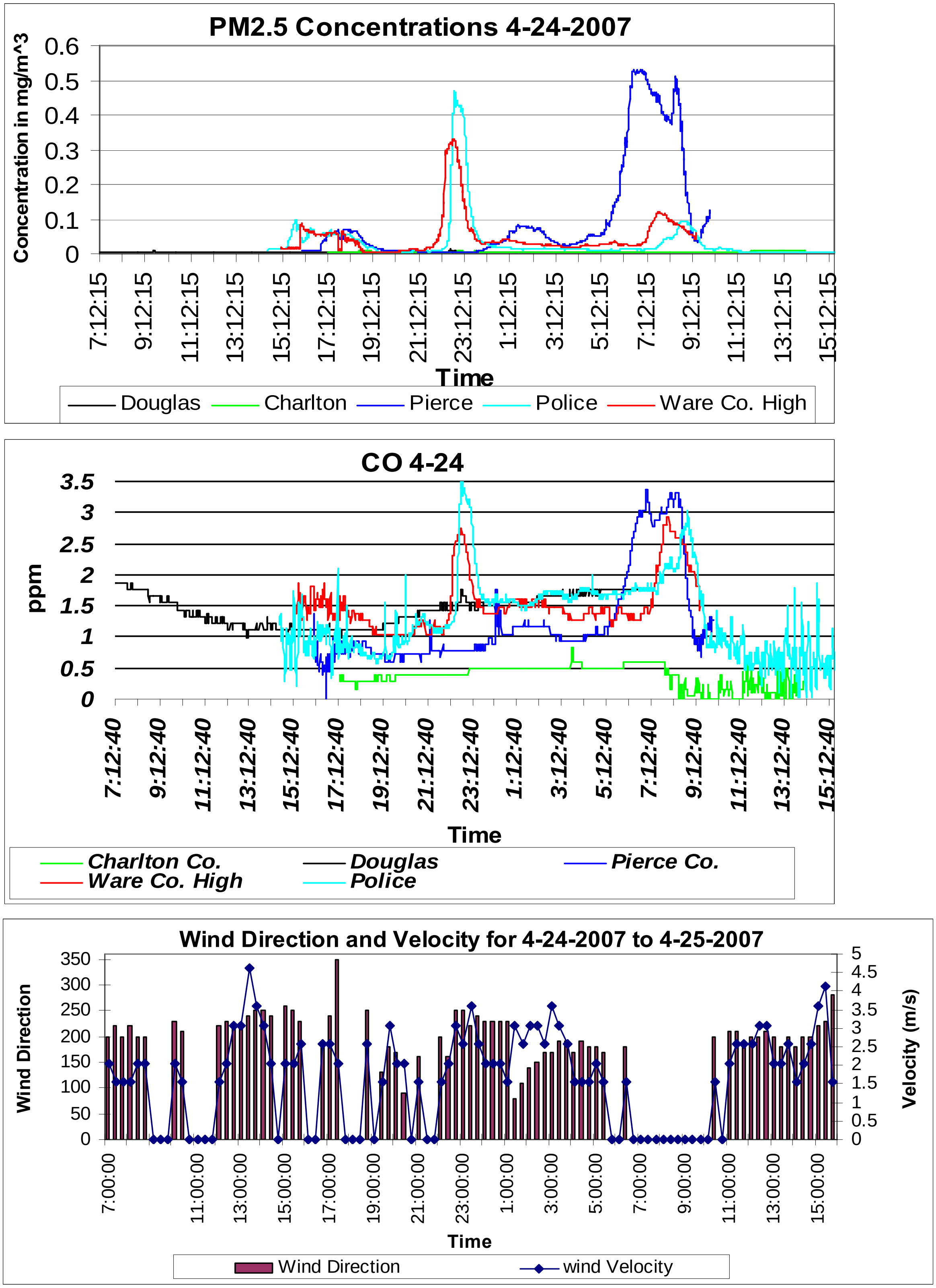


Figure 3-5: $PM_{2.5}$, CO, and wind data for April 24, 2007

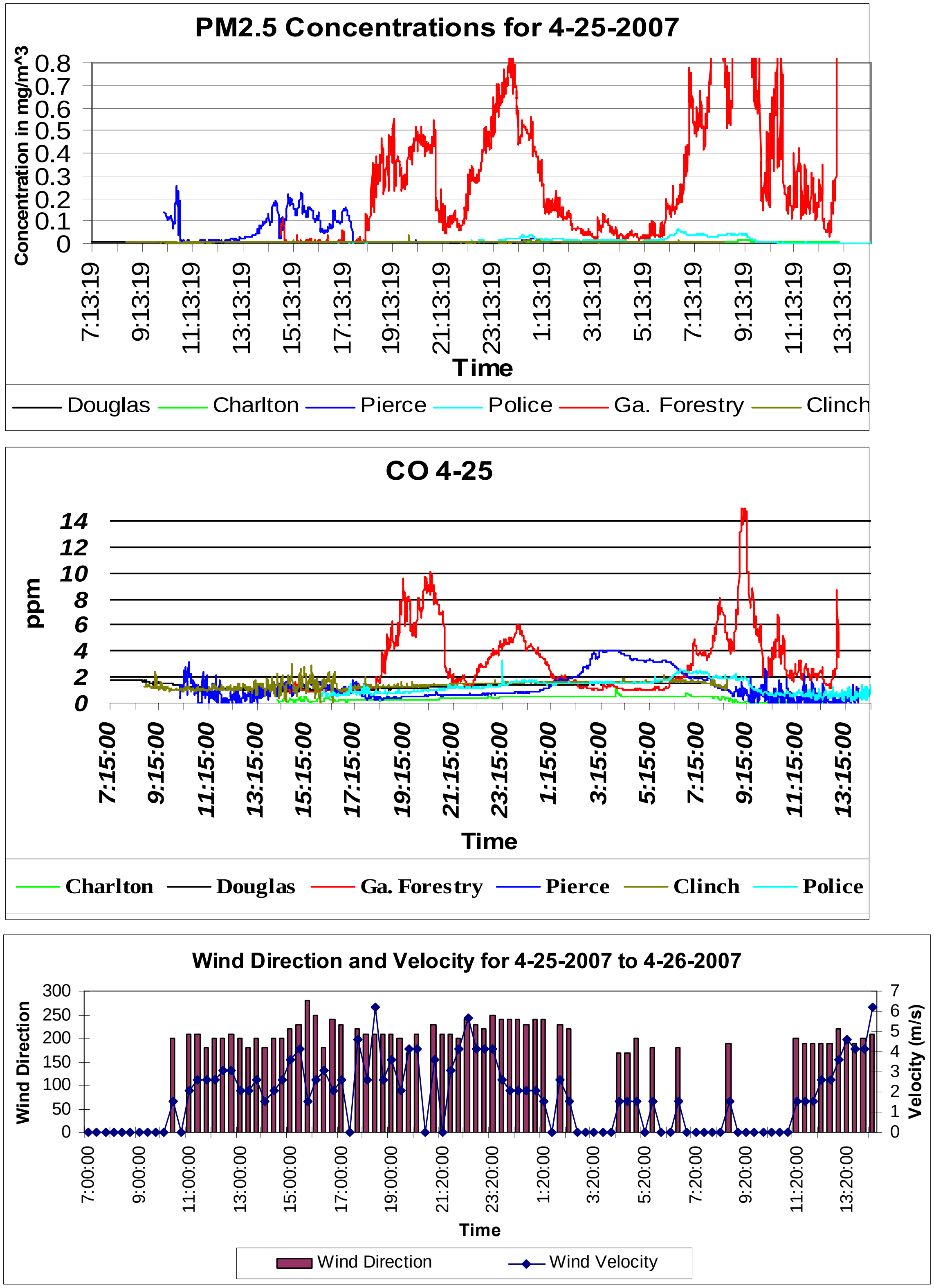
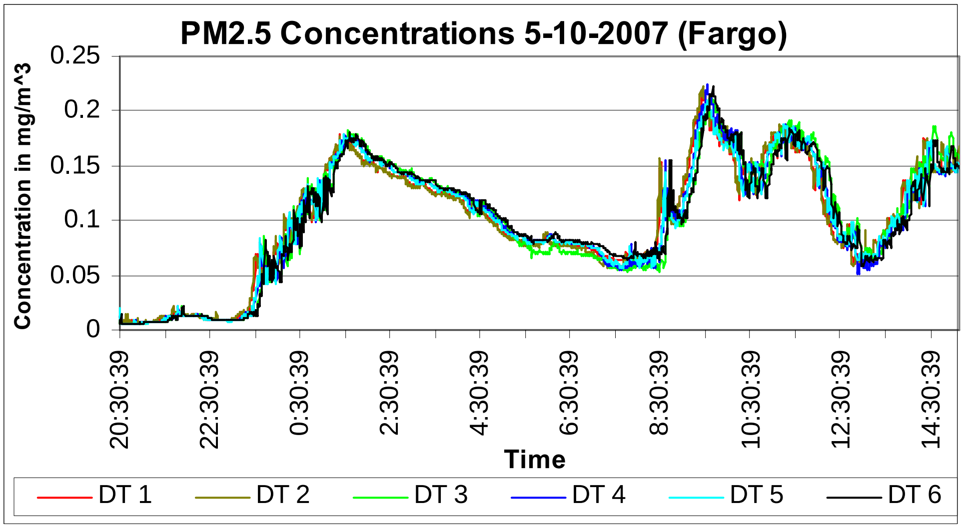
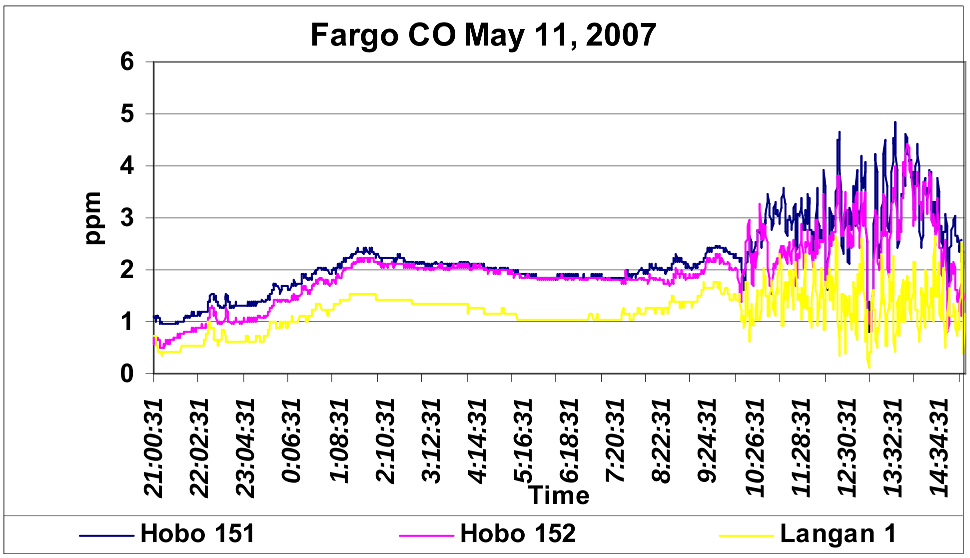


Figure 3-6: $PM_{2.5}$, CO, and wind data for April 25, 2007





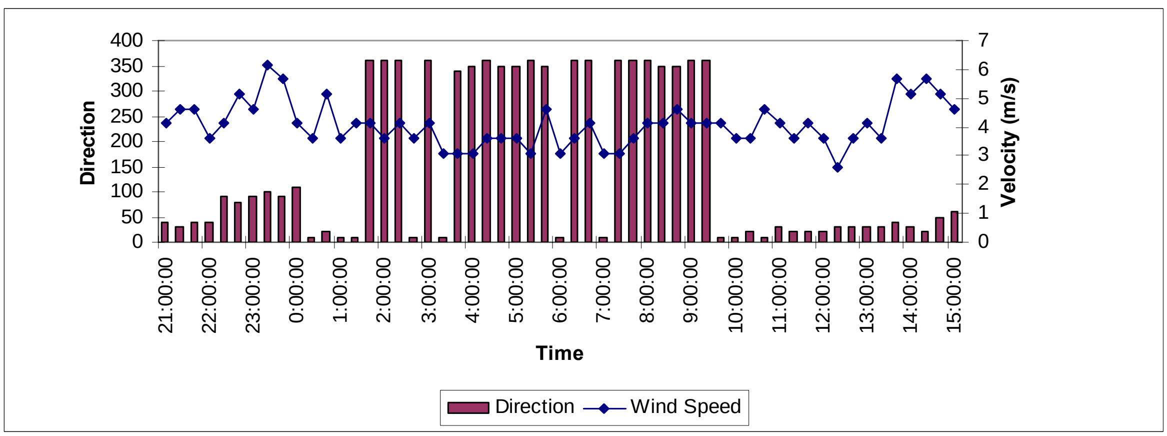


Figure 3-7: $PM_{2.5}$, CO, and wind data for May 10, 2007

CHAPTER 4

CONCLUSIONS

The results of this study suggest that $PM_{2.5}$ and CO levels in the community surrounding a wildfire are elevated. There are two factors that influence the levels of both constituents, location in relation to the fire and wind direction. The location in relation to the fire is shown by the closer to the fire you are the higher the exposure will be. Since the locations closest to the fire were evacuated, this factor is easily overcome. The wind direction data suggests that if the wind blows over the fire, locations directly in the path of the wind will experience elevated levels. One other factor that influences levels is nocturnal inversion, however since these happen at night when a majority of the general public is indoors asleep, this exposure would be minimal.

Eight sampling locations were over the 35 $\mu g/m^3$ deemed hazardous by the EPA, while no locations experienced levels over the EPA hazardous levels for CO. Both constituents of the smoke followed the same trends of increasing and decreasing. The fact that they follow the same trend could be used in future instances of wildfire monitoring as justification for monitoring $PM_{2.5}$ only, since $PM_{2.5}$ appears from this research to be of more concern than CO.

The highest levels observed were at the Georgia Forestry Commission at the Okeefenokee Swamp on April 25th, 2007. This location was frontline to the fire and showed what firefighters would be experiencing for their full shift at the fire. They are most definitely over the limit set forth by the EPA for 24 hour and used minimal respiratory protection. The general public on the other hand was at a decent remove from the fires, but still experience short periods of elevated levels and can be considered overexposed. The SDHD issued public service announcements and canceled public functions to help minimize exposure. However, some of the public either was unaware of the public service announcements or ignored them, so exposure to the public was still present, just that it was minimal. With a natural disaster being as close as it was to the communities, one would have to expect some exposure, so the aim should be to minimize exposure. That goal was accomplished by the work of the SDHD and other public officials.

THESIS SUMMARY

Wildfires are a natural process which is needed in many ecosystem to replenish nutrients and other beneficial effects. With the recent infringement of humans into the areas that are affected by wildfires, there becomes concern for the health of the individuals. The air being full of smoke is known to be detrimental to the health of humans and prolonged exposure to situations such as that are a growing concern.

Several studies show that particulate matter is a stimulus for precursors to cardiopulmonary disease (Tan et. al. 2000, Sutherland et. al. 2005, Schwartz et. al. 1989). Chronic obstructive pulmonary disease is also suggested to be associated with wildfire smoke (Sutherland et. al. 2005, Osman et. al. 2007), along with increased mortality from significant increases in particulate matter (Vedal et. al. 2006).

The research conducted here showed slightly elevated levels of $PM_{2.5}$ and CO with eight of twenty seven sampling locations being over the hazardous level of $PM_{2.5}$ and no sites above the hazardous level for CO. The two strongest contributing factors were location in relation to the fire and wind direction. Location is the easiest to overcome as getting further away from the fire is relatively easy. As wind cannot be controlled by man and can change at anytime it is the one that is hardest to control. Nocturnal inversion was a factor as well but the time frame in which these took place put the public at minimal risk.

The $PM_{2.5}$ data shows that there was increased $PM_{2.5}$ throughout the entire monitoring period, with episodes of elevated exposure in select regions on select days. The CO results track closely in time with the $PM_{2.5}$ results, although the CO levels generally did not elevate to levels of health concern. $PM_{2.5}$ levels were strongly correlated with how long the sampler was downwind of the fire, while the correlation between $PM_{2.5}$ levels and distance from the fire was negative, and not as strong.

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