Intensive Study of Ambient Carbon Dioxide Variability in Urban Atlanta

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INTENSIVE STUDY OF AMBIENT CARBON DIOXIDE VARIABILITY IN URBAN ATLANTA

by

BRIAN L. VANN

Under the Direction of Jeremy Diem

ABSTRACT

Urban areas contain multiple sources and sinks of carbon dioxide, yet spatial and temporal information explaining its variability, diurnal patterns, and effects from human activity are limited. The city of Atlanta, due to conflicting air masses, geographic location, and population growth, is as an excellent location to study carbon dioxide concentrations across its urban landscape. Mobile measurements of ambient CO$_2$ concentrations were obtained at 1.5m above ground level along a transect in winter 2010 within the perimeter of Atlanta. Analyses of winter 2010 CO$_2$ variability at GSU’s stationary CO$_2$ monitor was also explored. The results showed that CO$_2$ concentrations in Atlanta are highly variable. The GSU CO$_2$ station showed that weekday CO$_2$ concentrations to be significantly higher than weekends suggesting that anthropogenic emissions may be the cause.

INDEX WORDS: Anthropogenic, Atlanta, Carbon dioxide, Concentrations, Study area, Winter 2010
INTENSIVE STUDY OF AMBIENT CARBON DIOXIDE VARIABILITY IN URBAN ATLANTA

by

BRIAN L. VANN

Committee Chair: Jeremy Diem

Committee: Dajun Dai

Lawrence Kiage

Electronic Version Approved:

Office of Graduate Studies
College of Arts and Sciences
Georgia State University
May 2011
DEDICATION

I would like to give special thanks to my loving family. If not for their patience and support, I would have never had the resilience to continue my education. Thank you
ACKNOWLEDGEMENTS

I am ecstatic to have accomplished the Master of Arts program at Georgia State University. I would like to give my warmish wishes to fellow graduate students in the geography program. I deeply wish you all a long and prosperous future as we turn to the next page of our lives. To the many geography professors who had enough faith in my abilities. To Dr. Jeremy Diem who gave me the foresight and direction to see this project through until the end.

Thank you!
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1.0 INTRODUCTION

Anthropogenic CO$_2$ emissions have increased since the beginning of the 20$^{th}$ century and are a major component of global warming (Houghton 2001; Dyson 2005). Many believe that this important constituent of air is a threat to local community as well as worldwide residents (Jacobson 2008). CO$_2$, a naturally occurring gas is concentrated in the soil, water, and air, however, it is also a product of fossil fuel combustion. In large quantities, CO$_2$ is used as a raw material in many chemical, pharmaceuticals, and petroleum industries (Santoprete 2009). Automobiles and transport vehicles rank high in the production of CO$_2$ and in urban areas these concentrations accrue (Moriwaki and Kanda 2004). CO$_2$ mixes readily with other atmospheric constituents at the global scale, however, as some researchers have proposed, some urban areas show evidence of high carbon dioxide accumulation that are much larger than background concentrations (Stewart, Hameed et al. 1978). Therefore, the purpose of this study was to investigate the variability of ambient CO$_2$ concentrations in the winter of 2010 within the perimeter of Atlanta, Georgia.

1.1 CO$_2$ Emissions and Sequestration

The relationship between carbon dioxide and global surface temperatures are extremely complex (Hansen, Johnson et al. 1981). The idea that the burning of fossil fuels and a buildup of CO$_2$ in the atmosphere and their links to heat held at the surface of the earth stemmed from 19$^{th}$ century scientific work. Joseph Fourier (1878) was the first to recognize that the atmosphere may retain heat from radiation, while John Tyndall recognized the role that CO$_2$ plays in the process
(Fleming 2005). In 1986, the chemist Svante Arrhenius recognized how increased levels of atmospheric CO$_2$ produced from the burning of coal might raise the surface temperature of Earth. His initial estimate was that a doubling of atmospheric CO$_2$ would produce a rise in temperature of about 5°C (Khandekar, Murty et al. 2005). The World Meteorological Organization (NRDC 1995) estimates this value to be very close to today’s estimates using modern computers.

Carbon dioxide is a natural product of earth processes, yet humans are influencing it (Goudriaan and Ketner 1984; Falkowski, Scholes et al. 2000; Karl and Trenberth 2003). Royer, Wing et al. (2001) suggests ice core samples provide measures of atmospheric GHG concentrations from earlier periods in earth’s history. Atmospheric CO$_2$ concentrations increased from about 200 to 270 p.p.m.v. during the transition from the Last Glacial Maximum to the beginning of the Holocene (Indermühle, Stocker et al. 1999; Brook 2005). Since pre-industrialization, atmospheric carbon dioxide has risen from approximately 280 parts per million (ppm) to 382 in 2006, or a 35% increase (Quadrelli and Peterson 2007). For every gallon of gasoline burned in a vehicle, 25 pounds of carbon dioxide are produced along with carbon monoxides, sulfur dioxide, nitrogen dioxide, and particulate matter (Donohoe 2003). These gases contribute to the greenhouse effect, which has caused average worldwide temperatures to increase over the last one hundred years and dramatically increase annual incidences of deadly heat waves (Hansen 1988; Karl and Trenberth 2003; Schär, Vidale et al. 2004).

In the natural environment, carbon dioxide is necessary for most plants to produce food through photosynthesis (Chapin, Bloom et al. 1987). The concentration of atmospheric carbon dioxide rises and falls in seasonal patterns and exhibit a fluctuation range of about 6 ppm (Keeling, Bacastow et al. 1976). Evidence shows that the global concentration of CO$_2$ in the air has been increasing gradually over 60 years with a rate of increase of about 2ppm per year. This
estimation includes the decomposition of organic material, fermentation and digestion (Hansen, Sato et al. 2008).

1.2 The Greenhouse Effect of CO$_2$

Carbon dioxide is believed to be a driver for climate change and global warming (Mann 1998; Crowley 2000; Shackleton 2000). CO$_2$ and water vapor are the dominating gases controlling the greenhouse effect although many other gases exist in the atmosphere include methane (CH4), nitrous oxide (N2), and chlorofluorocarbons (CFC) (Watson, Meira Filho et al. 1992). Greenhouse gases are transparent to light energy from the sun but once it is re-emitted by the earth atmosphere system the greenhouse gases trap that energy. As these greenhouse gases increase in concentrations, the longwave energy accumulates in the troposphere and warms the earth (Cline 1991).

During most of the 20th century the idea of atmospheric CO$_2$ influences on surface temperatures received little attention. By the early 1980s, the concern that the earth was in fact warming and that it might be partly due to human activity led to the creation of the Intergovernmental Panel on Climate Change (Dyson 2005). Its directive is to assess research on climate and to provide relevant information to the global community. Successive IPCC reports have concluded with growing confidence that the Earth’s climate is indeed warming and that it could be due to anthropogenic causes- particularly the burning of fossil fuels which releases CO$_2$ into the atmosphere (Houghton, Ding et al. 2001). Although they do not disagree on the increased global concentrations of CO$_2$, some research has reviewed much of the scientific research concerning the consequences of increased levels of atmospheric carbon dioxide.
Robinson (2007) concluded that increased concentrations of CO₂ during the 20th and early 21st centuries have produced no lethal effects upon Earth’s climate. Additionally, they pose that CO₂ concentrations in Earth’s past and present lag temperature changes and could not have been the cause of warming.

1.3 CO₂ and Health

Although some research shows that CO₂ by itself does not affect human respiration directly and has therefore not been considered an air pollutant, per se, it does affect temperatures which feed back into air pollution. Jacobson (2008) produced a climate-air- pollution model that shows increases in fossil fuel surface ozone, carcinogens, and particulate matter which in turn increases asthma, cancer rates and death. He found that increases in temperature, water vapor, and ozone correlated positively with increases in CO₂ and suggested CO₂ domes had greater impacts from temperatures where the CO₂ was emitted. He also suggested that by reducing local CO₂ levels 300 to 1000 deaths per year caused by air pollution may be prevented. According to Valkama (2007), some research shows that carbon dioxide moderates ozone while other variables sometimes aggravate the effects of ozone.

A fairly consistent finding has been elevated levels of asthma hospitalizations or reduced respiratory capacity for children and adolescents residing near roadways with heavy traffic. In addition, increased temperature and CO₂ due to climate change likely will result in increased production of pollen and fungal spores that could exacerbate symptoms of allergic diseases (Gilmour, Jaakkola et al. 2006). Some researchers on public and health suggest a connection exists between residential proximity to roadways and health. “Pollution occurs through all stages
of transportation the production and use of vehicles, fuel, infrastructure and disposal” (Schweitzer, e.t.al. 2004:387).

Most studies have yielded results showing that low income and minority groups appear to bear a higher burden from pollution associated with transport in urban areas (Schweitzer 2004). Volmer (2001) shows similar results where not only has CO₂ from fossil fuel combustion via automobiles indirectly affected the health of the community but the distribution of pollution among low-income and minority communities have been shown to be relatively high. Inner-city, low-income residents have higher asthma rates and other respiratory illnesses.

Conflicting views of CO₂’s role in global climate change have challenged policy makers. Carbon dioxide is specifically listed by Congress as an air pollutant however much deliberation has been pursued over broad textual meanings in the statute. Even so, Maney (2005) states that an air pollutant under section 302 (g) classifies an air pollutant as any physical chemical substance that is emitted into the air is an air pollutant and that carbon dioxide satisfies that requirement.

Under President George W. Bush’s administration, the EPA caused a stir about the regulation of carbon dioxide by declaring that the agency does not have the authority to regulate the aforementioned gas and that it does not fall under the Clean Air Act of air pollution (Wiener 2006). In reaction to this, on October 23, 2003, the District of Columbia, American Samoa, twelve states, two cities, and fourteen public interest organizations filed petitions with the U.S. Court of Appeals to challenge the ruling. Bush claimed that the science was incomplete regarding CO₂ and climate change at that time, although most evidence showed the contrary. Paradoxically, Congress, in the latter part of the twentieth century, gave the EPA authority to
regulate any air pollutant that may have any “actual or potential” effect on the environment (Winters 2004).

1.4 The Global Impact of Urban CO₂

There has been an increasing concern over the possible impact of urbanization on global CO₂ emissions (Holtz-Eakin and Selden 1992; Galloway, Levy et al. 1994; Dietz and Rosa 1997). In 2004, carbon dioxide emissions contributed around 77 per cent of global anthropogenic greenhouse gas emissions. Shi (2003) provides evidence that population growth has been one of the major driving forces behind increasing carbon dioxide emissions worldwide over the last two decades. Using a data set of 93 countries spanning almost two decades, the study finds that global population change over the last two decades is associated with a 1.42% worldwide increase in CO₂ emissions.

Evidence (e.g. Idso, Idso et al. 2002; Jacobson 2010) suggests urban CO₂ domes exist over many large cities and that they are site and time dependent (Nasrallah, Balling Jr et al. 2003). Ziska, Gebhard et al (2003) showed that air temperature and atmospheric CO₂ are significantly higher in urban compared to rural areas. Patterns of urban development and transportation can significantly impact emissions considering the fact that nearly 40% of total U.S. carbon emissions are associated with residences and automobiles (Glaeser and Kahn 2010).

CO₂ emissions do come from places beyond the city. The assumption is that all emissions from industry, power stations, and transport come mostly come from cities (Velasco and Roth 2010). Dodman (2009) showed that emissions per capita from cities are usually lower than the average for the country in which they are located due to the fact that energy is usually produced
outside the city. Satterthwaite (2008) suggested that worldwide, less than half of all anthropogenic greenhouse gas emissions are generated within city boundaries. TABLE 1 shows how the US compares to other countries.

### TABLE 1 Country ranks by total and per-capita metric tons of CO₂ emissions produced in 2008.

<table>
<thead>
<tr>
<th>Country</th>
<th>MtCO₂e</th>
<th>Rank</th>
<th>Metric tons CO₂e Per Person</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>United States of America</td>
<td>4,980.90</td>
<td>1</td>
<td>16.4</td>
<td>5</td>
</tr>
<tr>
<td>European Community</td>
<td>3,061.60</td>
<td>2</td>
<td>7.8</td>
<td>15</td>
</tr>
<tr>
<td>Japan</td>
<td>1,135.60</td>
<td>3</td>
<td>8.9</td>
<td>13</td>
</tr>
<tr>
<td>Russian Federation</td>
<td>1,070.40</td>
<td>4</td>
<td>7.5</td>
<td>16</td>
</tr>
<tr>
<td>Germany</td>
<td>862.5</td>
<td>5</td>
<td>10.5</td>
<td>9</td>
</tr>
<tr>
<td>Canada</td>
<td>554.2</td>
<td>6</td>
<td>16.6</td>
<td>3</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>534.7</td>
<td>7</td>
<td>8.7</td>
<td>14</td>
</tr>
<tr>
<td>Australia</td>
<td>464</td>
<td>8</td>
<td>21.7</td>
<td>2</td>
</tr>
<tr>
<td>Italy</td>
<td>380.7</td>
<td>9</td>
<td>6.4</td>
<td>21</td>
</tr>
<tr>
<td>France</td>
<td>324.5</td>
<td>10</td>
<td>5.2</td>
<td>28</td>
</tr>
<tr>
<td>Ukraine</td>
<td>309.3</td>
<td>11</td>
<td>6.7</td>
<td>20</td>
</tr>
<tr>
<td>Spain</td>
<td>285.7</td>
<td>12</td>
<td>6.3</td>
<td>23</td>
</tr>
<tr>
<td>Poland</td>
<td>282.4</td>
<td>13</td>
<td>7.4</td>
<td>17</td>
</tr>
<tr>
<td>Turkey</td>
<td>216.5</td>
<td>14</td>
<td>2.9</td>
<td>37</td>
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<tr>
<td>Netherlands</td>
<td>178.1</td>
<td>15</td>
<td>10.8</td>
<td>7</td>
</tr>
<tr>
<td>Belgium</td>
<td>115.9</td>
<td>16</td>
<td>10.8</td>
<td>8</td>
</tr>
<tr>
<td>Czech Republic</td>
<td>115.8</td>
<td>17</td>
<td>11.1</td>
<td>6</td>
</tr>
<tr>
<td>Greece</td>
<td>106.6</td>
<td>18</td>
<td>9.5</td>
<td>12</td>
</tr>
<tr>
<td>Romania</td>
<td>67.3</td>
<td>19</td>
<td>3.1</td>
<td>35</td>
</tr>
<tr>
<td>Portugal</td>
<td>56.5</td>
<td>20</td>
<td>5.3</td>
<td>27</td>
</tr>
<tr>
<td>Austria</td>
<td>56</td>
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<td>6.7</td>
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<td>Denmark</td>
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<td>Hungary</td>
<td>51.7</td>
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<td>29</td>
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<td>Ireland</td>
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<tr>
<td>Bulgaria</td>
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<td>25</td>
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<td>Switzerland</td>
<td>45.3</td>
<td>26</td>
<td>5.9</td>
<td>25</td>
</tr>
<tr>
<td>Slovakia</td>
<td>37.7</td>
<td>27</td>
<td>7</td>
<td>18</td>
</tr>
</tbody>
</table>
1.5 Measuring CO₂ Across Urban Space

Remote sensing of urban landscapes may provide CO₂ emission information (Oda 2011). Although the spatial resolution may be somewhat large, remote sensing may offer alternative methods for locating emitters of CO₂ (DeFries, Achard et al. 2007). A satellite remote sensing concept based on measurements of reflected solar radiation shows that strong CO₂ point sources can be detected and their emissions quantified with existing technology. A spatial resolution of 2x2 km² with a precision of 0.5% (2ppm) or better is required to map the atmospheric CO₂ column distribution. Natural and anthropogenic CH₄ (methane) emission sources from land-fills, oil and gas fields, pipeline leaks, coal mines, mud volcanoes and marine seeps may also be quantified (Bovensmann, Buchwitz et al. 2010).

Some CO₂ monitors are stationary instruments placed at predetermined altitudes. Some analysts use devices attached to tall towers that obtain multiple gas concentration measurements in order to develop representative models of gas concentrations across space (Tans, Bakwin et al. 1996; George, David et al. 1999; Pattey, Edwards et al. 2006; Vermeulen, Pieterse et al. 2006). These representations are usually accomplished through eddy covariance techniques. In Mexico City, Velasco et al. (2005) used an eddy covariance (EC) flux system installed on a tall tower to obtain direct measurements of CO₂ emissions from an urban neighborhood. The CO₂ flux measurements showed a clear diurnal pattern with the highest emissions during the morning and the lowest emissions during nighttime. The measured fluxes of carbon dioxide were closely correlated to traffic patterns.

Multiple towers are beneficial for obtaining CO₂ gradients across landscapes. In Salt Lake City Valley, Utah, Pataki, Xu et al. (2007) measured urban to rural gradients of CO₂
concentrations at three tall tower locations from 2004 to 2006. Measurements were collected in the downtown business district, a residential neighborhood, and a non-urbanized rural location. CO₂ concentration measurements were conducted using LI-COR 7000 and LICOR 6262 infrared gas analyzers and CR23x Campbell Scientific dataloggers recording 2-minute running averages every 5 min. Results showed CO₂ concentrations exceeding 500 p.p.m. at the city center with much lower concentrations in the rural locations. The highest values in the city were measured in the wintertime under stable atmospheric conditions.

Mobile measurements of ambient CO₂ concentrations may provide better representations of urban sources and sinks. Many urban area air quality studies are monitored by relatively slow response instrumentation at fixed sites such as towers. Emission inventories are usually based on estimates rather than measurements, have poor temporal and spatial resolution, and are often outdated (Herndon, Jayne et al. 2005). The mobile laboratory can provide overall averaged emissions ratios for each exhaust plume encountered on a roadway. Averaged emission ratios can be used as a “road truth” check of mobile emissions in models. However, they may also be used to provide spatially and temporally emissions data to estimate pollutant exposures from roads or for input into models for air quality.

Obtaining CO₂ information across space using a mobile device are important to determine how carbon dioxide is influenced by spatial, meteorological, and land utilization variations (Henninger and Kuttler 2010). In Essen, Germany mobile measurements were taken during the winter (DJF) of 2002 and 2003 and summer 2003 (JJA) in different climatic conditions and at different times of the day to allow observations on CO₂ from the influence of vegetation and diurnal influences. Results showed a gradually yet steadily rising CO₂ dome from the rural to the urban area, the differences in CO₂ values in Essen were not as differentiated as
values were shown to be in other cities. The author recommends to conduct mobile transects at a minimum of two seasons with considerations of urban types of land utilization for proper seasonal and spatial variations of CO$_2$.

George, Ziska et al. (2007) performed transects across the Baltimore city center to the outer suburbs to obtain CO$_2$ concentration measurements. Atmospheric CO$_2$ significantly increased by an average of 66 ppm from the rural to the urban site. Air temperature was also consistently and significantly higher at the urban site compared to the suburban and rural sites.

Idso C.D. (2001) performed 4 transects on 14 consecutive days in the wintertime of 2000 across the metropolitan area of Phoenix, Arizona, obtaining atmospheric CO$_2$ concentrations. Measurements were taken prior to dawn and in the middle of the afternoon at a height of 2m above the ground. The existence of a strong but variable urban CO$_2$ dome was discovered which at one time exhibited a peak CO$_2$ concentration at the center of the city that was 75% greater than that of the surrounding rural area. In this winter study, peak city-center CO$_2$ concentrations measured in the hours just before dawn ranged from about 28 to 76% higher than what was normal for the surrounding desert, farmland and mountains, while the mean enhancement of the background CO$_2$ concentration at the city center was 43.3% for weekdays and 38.3% for weekends.

Berry et al. (1990) found by transects through Nottingham and nearby rural areas from December 1984 through July 1985 that winter months had somewhat different trends of CO$_2$ than summer. They found that in winter, small trends of increasing CO$_2$ and SO$_2$ towards the city center were observed at night and during the day but that the trend reversed at night in the summer.
2.0 RESEARCH QUESTION AND OBJECTIVES

The importance of urban areas affected by emissions from urban development and population growth leads to the following question:

How does the ambient CO$_2$ concentration vary within Atlanta’s “urban” landscape?

The above question drives the following major objectives in this research: (1) develop methods in which to obtain CO$_2$ concentration information across Atlanta; (2) assess spatial and temporal variability of carbon dioxide in the study area.

3.0 SUITABILITY OF THE STUDY AREA

Urban Atlanta is well suited to study spatial and temporal variations of CO$_2$. In 2002, combustion from fossil fuels to supply energy to U.S. residents were responsible for 90% of the greenhouse gases in the U.S. (Klara and Srivastava 2002). Georgia ranked 11 out of all states in the US among emitters of carbon dioxide in 2007 (EPA 2010). Georgia’s combined output of CO$_2$ emission from all sectors totaled 20,840,000 million metric tons (Gurney, Mendoza et al. 2009).

In Atlanta in 2002, 53.7% fossil fuel emissions were produced from electric production (Gurney 2009). At the outer perimeter of the Metropolitan Statistical Area of Atlanta, some of the largest emitters of carbon dioxide in the U.S. reside. Plant Scherer, located southeast of Atlanta by approximately 92 kilometers, is the second largest producer of carbon dioxide in the
nation, while Plant Bowen, only approximately 65 kilometers to the northwest of Atlanta, ranked number one in the nation in CO₂ emissions (Wu 2003).

Automobiles and transport vehicles supply Atlanta with a large quantity of CO₂ given that thousands of automobiles traverse into the perimeter of Atlanta each day (Henderson 2004). In 2005, out of the top 100 metro areas in the U.S., Atlanta ranked number 5 in total vehicle miles traveled and CO₂ emissions produced from those miles (see TABLE 2). In Atlanta, 28.9% of emissions from carbon dioxide originate from ground transport, and a total of 17.2% from residential, industrial, commercial, and aircraft (Gurney 2009).

<table>
<thead>
<tr>
<th>Rank</th>
<th>Top 100 Metro Areas in US (2005)</th>
<th>VMT (million)</th>
<th>CO₂ (mmTons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>New York</td>
<td>110,810.40</td>
<td>15.515</td>
</tr>
<tr>
<td>2</td>
<td>Los Angeles</td>
<td>99,231.40</td>
<td>13.217</td>
</tr>
<tr>
<td>3</td>
<td>Chicago</td>
<td>71,232.10</td>
<td>10.694</td>
</tr>
<tr>
<td>4</td>
<td>Dallas-Fort</td>
<td>56,443.60</td>
<td>8.185</td>
</tr>
<tr>
<td>5</td>
<td>Atlanta-Sandy</td>
<td>55,685.70</td>
<td>8.123</td>
</tr>
<tr>
<td>6</td>
<td>Riverside-San Bernardino</td>
<td>48,121.20</td>
<td>7.371</td>
</tr>
<tr>
<td>7</td>
<td>Lauderdale-Miami</td>
<td>50,179.00</td>
<td>7.024</td>
</tr>
<tr>
<td>8</td>
<td>Houston</td>
<td>49,073.40</td>
<td>7.003</td>
</tr>
<tr>
<td>9</td>
<td>Washington DC</td>
<td>45,393.20</td>
<td>6.077</td>
</tr>
<tr>
<td>10</td>
<td>Detroit</td>
<td>44,605.40</td>
<td>6.037</td>
</tr>
</tbody>
</table>

Table 2: Top 10 metro areas in the U.S. by vehicle miles traveled and the resulting CO₂ produced from those miles in million metric tons (Brown and Logan 2008).
In retrospect to the prior observations, the study area was limited geographically to urban Atlanta to explore how concentrations of CO\textsubscript{2} react in an urban environment in the southeast region. CO\textsubscript{2} concentrations across the Atlanta area should not only have a propensity to show variability of CO\textsubscript{2} from fossil fuel combustion but also the likelihood to contain concentration variations of CO\textsubscript{2} from soil, concrete manufacture, vegetation, and other sources and sinks. Similar to Henninger et al. (2010) and Idso’s (2001) research, the analysis here involved collecting CO\textsubscript{2} data in proximity to the city center via transects. Other researchers have found significant variability of CO\textsubscript{2} concentrations across urban landscapes.

Idso et al. (2000) evaluated the strength of Phoenix, Arizona’s CO\textsubscript{2} dome by comparing nearby rural CO\textsubscript{2} concentrations to Phoenix’s urban areas. They used 369 ppm as the baseline in which to compare due to the fact that it was the lowest readings of CO\textsubscript{2} from the most “pristine” of their transects. Although their base value was calculated to be within .17% of Mauna Loa’s global mean background concentrations for that same year (January 2000), more regionalized rural values of CO\textsubscript{2} for Atlanta was used.

Additionally, random sampling techniques were used in the examination of Atlanta’s urban CO\textsubscript{2}. This method of data collection and analysis has multiple inherent values. For one, it enables a “ground truth” analysis of CO\textsubscript{2} concentrations by the removal of bias from close proximity to roadways but it also enables a representation of the CO\textsubscript{2} concentrations within Atlanta- one that was lacking.
4.0 METHODOLOGY

4.1 Instruments Used in the Study

Portable devices used in the data collection were obtained from the Geosciences department at Georgia State University in Atlanta, Georgia. GE Telaire 7001 Dual Beam Absorption Infrared™ handheld CO₂ monitors used in this study use a sensor capable of an accuracy of ±50 ppm or ±5% of reading up to 5000 ppm. Its pressure dependence is 0.13% of reading per mm Hg, which may be corrected via user input for elevation. The Telaires were calibrated for elevation per instructions from the manufacturer at an elevation of 300m ASL (MicroDAQ.com). The Telaires were tested for CO₂ calibration prior to data collection by using the prescribed method from the manufacturer. Using the “zero” calibration gas (N₂), the Telaires were tested for zero calibration by injecting 7 lbs/sq.inch of N₂ into the Telaire’s CO₂ sensor. Once fully primed with the calibrating gas, the Telaire required a resetting and re-zeroing procedure prescribed by the manufacturer.

CO₂ information obtained by the Telaires was stored on dataloggers. The HOBO datalogger is a 4-Channel device capable of measuring temperature and humidity along with 2 additional external inputs ideal for Telaire 7001’s. The logger can log and record up to 7,943 samples and readings, features a user selectable sampling interval of 0.5 seconds to 9 hours, a programmable start date/time, a user replaceable battery, and multiple operating modes. The software Box Car 3.7 for Windows is required to select sampling intervals, set the start time and a memory mode, verify proper logger operation, syncing the logger clock to the computer, and to check battery status (Onset Computer 2011). The CO₂ concentration values read by the Telaires
are sent to the dataloggers via the voltage reading and is then stored in the datalogger memory. The attributes included in each column of data were represented under the headings of Date/Time, Temp (°F/°C) RH (%), Dew Point (°F/°C), Abs Humidity (gm/M3), Uncomp RH (%), Voltage (V) (*3), and Voltage (V) (*4). The Voltage (V) (*3), and Voltage (V) (*4) attributes maintained in the datasets represent the current supplied to the dataloggers by each attached Telaire. The voltage fields are used to calculate the resulting CO₂ concentrations by multiplying each sample by 1000.

Global positioning systems were used to log temporal information as well as spatial data. Using a Garmin Oregon 300 handheld GPS, time stamps were used to geo-reference route and sample stations corresponding to HOBO datalogger temporal information. GPS data was obtained at a frequency varying between 1 and 14 seconds along the route and at sample stations and consisted of coordinate information, Local Standard Time (LST) stamps, GMT, elevation, azimuth, and date. CO₂ information contained in the dataloggers was imported into the point feature attribute table to display the georeferenced values in ESRI’S ArcMap.

Georgia State University (GSU) provided data representing CO₂ concentrations at the city core. The GSU rooftop station consists of a LICOR LI-820 CO₂ Analyzer that obtains readings of CO₂ concentrations. It is a non-dispersive infrared gas analyzer based upon a single path, dual wavelength, and thermostatically controlled infrared detection system. The LI-820 has an accuracy of less than 3% of reading, while less than 1 ppm of RMS noise at 370 ppm. The GSU rooftop CO₂ analyzer measures ambient CO₂ concentration every 10 seconds; therefore, each hourly value is the mean of 360 measurements. The datalogger in which the LICOR sends its data to stores the measurements as 1 minute means values in a text file. It records and displays
CO₂ concentrations in parts per million (ppm). The LICOR was calibrated prior to the study per manufacturers’ recommendations.

Prior to sampling throughout the study area, testing for differences in the devices used to obtain CO₂ concentration measurements were made. The GSU LICOR station CO₂ measurements were compared to three Telaire CO₂ handhelds that were to be used in the Atlanta study. The LICOR rooftop CO₂ monitor has a built in data port that allows the user to connect a PC to perform a variety of functions. Once connections are secured via serial port, the LI-820 software is launched to access live feed from the LICOR. The user interface displays the CO₂ concentrations being analyzed by the device. If calibration is required, the former procedure is followed, however, either a “span” gas of a specific CO₂ concentration is connected into the LICOR’s input connection or a zero gas may be used. After the gas has purged the system, the specific procedures required to calibrate the LICOR should be followed in the LICOR LI-820 manual. After checking the LICOR for calibration precision, the LICOR and 3 Telaire CO₂ monitors obtained CO₂ concentration information within 1.5 meters of each other for 11 consecutive minutes while obtaining CO₂ concentration information.

4.2 Spatial Sampling

Secondary data was used as the basemap for the study area. Spatial data representing the study domain was obtained from a geospatial database. The Georgia GIS Clearinghouse organizes spatial data from a variety of sources within its database (http://gis.state.ga.us/). Through the Georgia GIS Clearinghouse Library, The Atlanta Region Information System (ARIS) Volume 1c provided basemap expressway, street, and county boundary shapefile datasets
for the state of Georgia. All had a spatial reference of GCS North American 1983 with a projection of State Plane Georgia West FIPS 1002 Feet.

Shapefile data were modified relevant to the study area. Street, expressway, and county boundary shapefiles were imported into ESRI’s ArcGIS Desktop to visualize extent of the streets, spatial congruency, and relevancy to the study area. The street and expressway data extended beyond the study area, thus, geoprocessing was performed. A polygon layer was created using ESRI’s ArcMap to enable clipping of unwanted features in the streets and expressways dataset. A polygon layer shapefile was created and edited by creating a new feature that followed the outer perimeter of Atlanta at I-285 representing the study extent. The polygon shapefile enabled the software the ability to “clip off” any features that were outside the study domain.

Using the 285 corridor surrounding Atlanta as the study boundary, a grid was produced and centered on the study domain to create a systematic sampling procedure (see FIGURE 5). The grid was developed using an Arcscript from Jenness Labs available at http://www.jennessent.com/arcgis/repeat_shapes.htm. “Repeating Shapes” generated a grid of separate equal sized square grid cells of repeating shapes overlying the study area.

Random point stations within the sample area were generated to allow CO2 sampling stations to be geographically located. The point feature locations were generated within the study domain using an ArcGIS scripting tool. The free tool, known as Hawth’s Analysis Tools for ArcGIS available at http://www.spatialecology.com/htools/download.php, was developed in the context of ecological application, however, it is also useful for a broad range of other applications invested in spatial statistics. The point stations at each vertex were then optimized for randomness by generating random value syntax and using those values to relocate each
vertices’ an easting and northing direction. Coordinate information for each sample station was recorded and used for georeferencing. Sample stations were buffered by 750m to obtain a larger dataset of CO$_2$ information while also serving as a temporal control for the analysis. The sample stations that fell outside the study area were removed.

Google Maps provided the routes to acquire CO$_2$ data both between the sample stations and the transect. Routes for transects to sampling stations were designed to enable collection of CO$_2$ concentration information that would show variability within the study area. Route information was captured by utilizing the “Get Directions” tool in Google Maps. Google Maps generated a directional map that consisted of the shortest and fastest route between the sampling stations, however, routes were edited weave on and off major roadways. This method enabled the acquisition of CO$_2$ data away from and in proximity to known emitters of CO$_2$.

CO$_2$ data was obtained at the sample stations and along the transect throughout the study area. At intervals of 9 seconds, 3 Telaires simultaneously sampled ambient CO$_2$ concentrations along the transect at 1.5 meters above ground level in an open air environment. Temporal information from the GPS was matched with samples obtained by the Telaires. At each interval of CO$_2$ sampling by the three Telaires the measurements were averaged. Statistical tests were performed to evaluate if statistically significant ($\alpha=0.05$) differences existed between the CO$_2$ concentrations at the buffered sample stations and the GSU LICOR station at their respective times.
4.3 Regional Mean Carbon Dioxide

Regional CO₂ concentration data used in the analysis were obtained from the NOAA ESRL Tall Tower Network or, more specifically, the Beech Island, South Carolina Tall Tower. The Beech Island, South Carolina station (FIGURE 1) is representative of the CO₂ concentrations in the southeast region due to the fact that it is in proximity to anthropogenic sources in the southeast. In contrast to the former, Mauna Loa’s global mean background concentrations are far from anthropogenic sources such as those found in the southeastern United States. The CO₂ abundance is given as a mole fraction in units of parts per million (ppm). The value for the datasets corresponds to the number of CO₂ molecules per 1 million molecules of dry air (Andrews 2009). Statistical tests were employed to determine if significant differences exist in the means of CO₂ from the regional background levels and from the GSU LICOR CO₂ station. The data extracted were from a 2009 DJF winter season available from esrl.noaa.gov/gmd. The Beech Island Tall Tower’s data is comprised of CO₂ concentration data obtained at 5 minute intervals from any one of three instruments at 31, 61, and 305 meters above ground level. FIGURE 2 is a time series graph of CO₂ concentrations obtained by the tower since 2008 showing seasonal variations.
SCT: NOAA/ESRL began continuous measurements of CO2 and CO at the "South Carolina Tower" in August 2008 as part of a partnership with the Department of Energy Office of Science to expand carbon cycle research at the Savannah River Site. The SCT site takes advantage of a pre-existing comprehensive meteorological network in the region that is operated by the Savannah River National Laboratory. The SRNL network includes 3-dimensional sonic anemometers and fast response CO2 and H2O sensors at each of the sampling heights on the tower that are now also used for the NOAA CO2 and CO measurements. This location samples the southeastern US within a mixed use agricultural, residential, and industrial zone. Partners: Savannah River National Laboratory (Matt Parker), University of Georgia (Professor Monique LeClerc).

Courtesy of: http://www.esrl.noaa.gov/gmd/ecoat/towers/index.html

FIGURE 1 South Carolina Tower in Beech Island, South Carolina where measurements are taken at three different altitudes.

A CO2 time series from Beech Island, South Carolina via tall towers. Data shown may be measurements of air collected approximately weekly in glass containers and returned to GMD for analysis or averages from air sampled semi-continuously at a GMD baseline observatory. Symbols are thought to be regionally representative. Data shown in ORANGE are preliminary. All other data have undergone rigorous quality assurance and are freely available from GMD, CDIAC, and WMO WDCGG.

Source: http://www.esrl.noaa.gov/gmd/dw/iadw/graph.php?

FIGURE 2 Graphed time series of CO2 concentrations at the Beech Island site.
4.4 Winter 2010 at Georgia State University

The study day CO\textsubscript{2} concentration information at the GSU station was compared to the DJF winter of 2010. Statistical testing was employed to observe whether significant differences in CO\textsubscript{2} existed between the study day and all days in winter 2010. Data obtained from the GSU LICOR station were imported into a spreadsheet where data were extracted that coincided with all days in DJF, as well as the study day. The study day was also compared to weekdays in the DJF 2010 season. Significance levels were set at \( \alpha=0.05 \).

Winter 2010 weekday and weekend CO\textsubscript{2} concentration information was explored at the Georgia State LICOR station. To determine if statistically significant differences existed in ambient CO\textsubscript{2} concentrations at the LICOR station between weekends and weekdays, data were extracted and imported into statistical software. Winter 2010 weekend 24 hour days were extracted from the DJF LICOR one hour mean datasets, as was the weekday 24 hour days. The analysis was performed at the \( \alpha=0.05 \) significance level.

5.0 RESULTS

5.1 Instrumentation

Results showed instrumentation differences were minimal. Data from the three Telaires resulted in 33 CO\textsubscript{2} concentration values and were averaged for each minute. The resulting datasets were imported into the Mann Whitney U Test that revealed if differences exist in the two sets of data. It was found that the carbon dioxide measurements obtained by the instruments
were not significantly different from one another. A graphical representation of the two datasets may be seen in FIGURE 3

![Graph comparing the three Telaires used in the study with the LICOR station.](image)

**FIGURE 3** Graph comparing the three Telaires used in the study with the LICOR station.

### 5.2 Spatial Sampling

The systematic sampling procedure resulted in 14 random locations in which to collect CO₂ concentration information within the study area. 30 square grid cells of 42.25 km² each were produced with respect to the boundary polygon shapefile that followed the outer perimeter of Atlanta. A total of 42 point feature shapefiles with coordinate information were generated and placed at the lower left vertices of each grid cell by specifying a point spacing of 21343 ft. Subsequently, to create systematic random sampling, station shapefiles were moved an easting direction of 6009 feet and a northing direction of 2154 feet. The sample stations that fell outside the study area were removed. The study area along with the grid, randomly placed point feature shapefiles, and buffered sample stations may be seen in FIGURES 4, 5, and 6, respectively.
FIGURE 4 The study area within Atlanta’s perimeter
FIGURE 5 Resulting sampling stations from the systematic sampling procedure
FIGURE 6 750m buffered sampling stations
Google Maps produced routes between sampling stations that meandered on and off major roadways. Beginning with a location west of Atlanta at N33.75326 W84.70935, traversing to sample station location 12 and 13, then to station 11, 7, 4, 1, 0, 2, 3, 6, 5, 9, 10, and 8. Sample station I.D. information along with its corresponding coordinates in decimal degrees and Local Standard Time are listed in TABLE 3. The Google Map for the route may be seen in FIGURE 7.

TABLE 3 Station identifier along with its respective coordinates and local time that each station was sampled.

<table>
<thead>
<tr>
<th>STATION ID</th>
<th>STATION LAT/LONG DD</th>
<th>LST</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>33.67112/-84.45419</td>
<td>11:43-11:51</td>
</tr>
<tr>
<td>13</td>
<td>33.67126/-84.38356</td>
<td>11:58-12:05</td>
</tr>
<tr>
<td>11</td>
<td>33.72993/-84.24368</td>
<td>12:18-12:24</td>
</tr>
<tr>
<td>7</td>
<td>33.78892/-84.31445</td>
<td>12:39-12:42</td>
</tr>
<tr>
<td>4</td>
<td>33.84796/-84.31389</td>
<td>12:52-13:00</td>
</tr>
<tr>
<td>1</td>
<td>33.90646/-84.31400</td>
<td>13:16-13:21</td>
</tr>
<tr>
<td>0</td>
<td>33.90472/-84.38350</td>
<td>13:27-13:33</td>
</tr>
<tr>
<td>2</td>
<td>33.84826/-84.45543</td>
<td>13:43-13:51</td>
</tr>
<tr>
<td>3</td>
<td>33.84786/-84.38401</td>
<td>14:00-14:08</td>
</tr>
<tr>
<td>6</td>
<td>33.78881/-84.38452</td>
<td>14:18-14:24</td>
</tr>
<tr>
<td>5</td>
<td>33.78867/-84.45458</td>
<td>14:35-14:41</td>
</tr>
<tr>
<td>9</td>
<td>33.72976/-84.38371</td>
<td>14:54-14:59</td>
</tr>
<tr>
<td>10</td>
<td>33.72932/-84.31369</td>
<td>15:10-15:16</td>
</tr>
<tr>
<td>8</td>
<td>33.73016/-84.45504</td>
<td>15:28-15:33</td>
</tr>
</tbody>
</table>
On February the 9th 2011 in Atlanta, Georgia, primary data representing CO₂ concentrations along the transect was obtained from 11:43 am to 15:33pm. Data obtained within the buffered sample stations resulted in temporal lengths between 4 and 9 minutes of data accumulation and resulted in 287 averaged CO₂ concentration measurements. Data acquired throughout the entire transect resulted in 1540 averaged CO₂ values. The distribution histograms for the 287 CO₂ concentrations within the buffered sample stations along with their descriptive
statistics may be seen in FIGURE 8 and TABLE 4, respectively. FIGURE 9 shows the data distributions for each buffered station. FIGURE 10 is a histogram of the CO₂ data along the entire transect.

TABLE 4 Descriptive statistics on CO₂ data obtained while within buffered zones.

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Statistic</th>
<th>Std. Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>429.334495</td>
<td>1.3973523</td>
</tr>
<tr>
<td>95% Confidence Interval for Mean</td>
<td>426.584096</td>
<td>432.084894</td>
</tr>
<tr>
<td>5% Trimmed Mean</td>
<td>428.970641</td>
<td></td>
</tr>
<tr>
<td>Median</td>
<td>428.000000</td>
<td></td>
</tr>
<tr>
<td>Variance</td>
<td>560.394</td>
<td></td>
</tr>
<tr>
<td>Std. Deviation</td>
<td>23.6726493</td>
<td></td>
</tr>
<tr>
<td>Minimum</td>
<td>366.3333</td>
<td></td>
</tr>
<tr>
<td>Maximum</td>
<td>489.6667</td>
<td></td>
</tr>
<tr>
<td>Range</td>
<td>123.3333</td>
<td></td>
</tr>
</tbody>
</table>

FIGURE 8 Histogram of all CO₂ values that were obtained while inside station buffer zones.
FIGURE 9 Individual histograms of the CO$_2$ values obtained while within each station’s buffer zone.
Since the data within the buffered sample stations were not normally distributed, the Mann Whitney U Test was utilized to compare the 14 buffered sample stations CO$_2$ data to the GSU LICOR station at their respective times. At an $\alpha = 0.05$ level of significance, there was enough evidence to conclude that there is a significant difference in the median CO$_2$ concentration values between the Georgia State University CO$_2$ monitoring station and stations 13, 7, 4, 1, 0, 2, 3, and 6. TABLE 5 represents the results from the Mann-Whitney U Test along with the CO$_2$ values averaged from each sampling. The transect map in FIGURE 11 shows absolute CO$_2$ values obtained throughout the transect. FIGURE 12 represents the CO$_2$ values obtained within each buffered station. FIGURE 13 is a graphical representation of the difference between the CO$_2$ data from the sampling stations and the LICOR station at Georgia State University.
TABLE 5 Station I.D. along with CO₂ values obtained while within each buffer zone compared to GSU stations’ measurements at corresponding times. The results from the Mann-Whitney U test are also displayed.

<table>
<thead>
<tr>
<th>Station I.D.</th>
<th>Telaire CO₂</th>
<th>Licor CO₂</th>
<th>Percent Difference</th>
<th>P value (two tailed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>406</td>
<td>417</td>
<td>-3%</td>
<td>.145</td>
</tr>
<tr>
<td>13</td>
<td>402</td>
<td>418</td>
<td>-4%</td>
<td>.025</td>
</tr>
<tr>
<td>11</td>
<td>415</td>
<td>402</td>
<td>3%</td>
<td>.360</td>
</tr>
<tr>
<td>7</td>
<td>445</td>
<td>409</td>
<td>9%</td>
<td>.000</td>
</tr>
<tr>
<td>4</td>
<td>457</td>
<td>409</td>
<td>12%</td>
<td>.000</td>
</tr>
<tr>
<td>1</td>
<td>454</td>
<td>405</td>
<td>12%</td>
<td>.001</td>
</tr>
<tr>
<td>0</td>
<td>434</td>
<td>410</td>
<td>6%</td>
<td>.012</td>
</tr>
<tr>
<td>2</td>
<td>432</td>
<td>406</td>
<td>6%</td>
<td>.003</td>
</tr>
<tr>
<td>3</td>
<td>453</td>
<td>408</td>
<td>11%</td>
<td>.000</td>
</tr>
<tr>
<td>6</td>
<td>450</td>
<td>412</td>
<td>9%</td>
<td>.000</td>
</tr>
<tr>
<td>5</td>
<td>414</td>
<td>419</td>
<td>-1%</td>
<td>.445</td>
</tr>
<tr>
<td>9</td>
<td>412</td>
<td>414</td>
<td>0%</td>
<td>.448</td>
</tr>
<tr>
<td>10</td>
<td>415</td>
<td>425</td>
<td>-2%</td>
<td>.220</td>
</tr>
<tr>
<td>8</td>
<td>424</td>
<td>419</td>
<td>1%</td>
<td>.455</td>
</tr>
</tbody>
</table>
Map of Atlanta Carbon Dioxide Transect

**February 9, 2011**

**FIGURE 11** Mapped CO$_2$ concentration values along the transect.
FIGURE 12 CO₂ concentration values obtained while within buffered sample station zones
The Beech Island Tall Tower dataset contained null values of -999.99 that were removed due to the fact that they were invalid data. The resulting dataset for Beech Island consisted of 36,210 CO$_2$ measurements used in the analysis. The GSU LICOR station had 5 minute mean data totaling 25,920 data samples. A histogram along with descriptive statistics for the Beech Island CO$_2$ dataset may be seen in FIGURE 14. The two datasets produced a significant $t$ value of -156.51, $p\leq0.05$. An examination of the means revealed that CO$_2$ concentrations were higher at the LICOR station ($\bar{x}=413$) than Beech Island ($\bar{x}=399$). Using a Student’s $t$ Test at $\alpha=0.05$ level of significance, there is enough evidence to conclude that there is a significant difference in
the mean CO₂ concentration values between the mean of Beech Creek’s Tall Tower and Georgia State’s LICOR station for the winter of 2010.

![Graph showing CO₂ concentration values with statistics]

FIGURE 14 Histogram and descriptive statistics from the South Carolina Tower CO₂ dataset.

### 5.4 The Study Day Compared to All Days in Winter 2010

The Student’s t Test showed that overall there is evidence of significant differences between CO₂ during days in DJF and February the 9th \((t = 16.280; \ p \leq 0.05)\). The study day CO₂ \(\bar{x}\) was calculated to be 421, while the \(\bar{x}\) for the DJF 2010 season was at 413. TABLE 6 shows the results from the test. Hourly data was extracted to provide a visual representation of the differences and may be seen in figure FIGURE 15. The 90 day trend for the 2010 winter season is presented in FIGURE 16.
**FIGURE 15** 90 day $\bar{x}$ for each hour in DJF 2010 compared to the study day

**TABLE 6** Student’s $t$ Test results comparing differences of the means between DJF and the study day.

<table>
<thead>
<tr>
<th>Group</th>
<th>N</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>Std. Error Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO2ALLDAYS</td>
<td>1DJF</td>
<td>129600</td>
<td>412.80</td>
<td>18.708</td>
</tr>
<tr>
<td></td>
<td>2 Feb 9</td>
<td>1440</td>
<td>421.18</td>
<td>19.431</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Levene's Test for Equality of Variances</th>
<th>t-test for Equality of Means</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>Sig.</td>
</tr>
<tr>
<td>---</td>
<td>------</td>
</tr>
<tr>
<td>CO2ALLDAYS Equal variances assumed</td>
<td>50.668</td>
</tr>
</tbody>
</table>
FIGURE 16 Variability of CO₂ concentrations from December 1, 2010 to February 28, 2011 at the LICOR station

5.5 The Study Day and Weekdays of Winter 2010

Differences existed between the study day and weekday days in winter 2010. The results of the Student’s t Test revealed that there is enough evidence to conclude that on February the 9\textsuperscript{th} at the $\alpha=0.05$ level there was a significant difference in CO₂ concentrations compared to all other weekdays in the 2010 Winter season ($t= -5.075; p<0.05$). TABLE 7 shows the results from the Student’s $t$ Test. FIGURE 17 shows a graphical representation of the differences in CO₂ concentrations obtained on February 9\textsuperscript{th} and weekday in DJF.
FIGURE 17 90 day averages of CO$_2$ concentrations for every hour at the LICOR station in comparison to the study day

TABLE 7 Statistical results from the Student’s $t$ Test comparing differences in the means between the study day and weekdays in DJF 2010.

<table>
<thead>
<tr>
<th>Weekdays VS 02/09/10 Group Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group</td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td>WeekdayAvg</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Levene’s Test for Equality of Variances</th>
<th>t-test for Equality of Means</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>Sig.</td>
</tr>
<tr>
<td>---</td>
<td>------</td>
</tr>
<tr>
<td>WeekdayAvg</td>
<td>Equal variances assumed</td>
</tr>
</tbody>
</table>

**Figure Caption:**

FIGURE 17 90 day averages of CO$_2$ concentrations for every hour at the LICOR station in comparison to the study day.
5.6 Weekday and Weekend CO₂

The resulting dataset consisted of 624 hours of weekend CO₂ concentration data along with 1536 hours of weekday CO₂ concentration values. The histogram of the averaged 1 minute mean data may be seen in FIGURE 18. Using the Student’s t Test, weekday and weekend ambient CO₂ concentrations during DJF 2010 produced a significant t value of -3.067, p≤0.05. An examination of the means revealed that CO₂ concentrations were higher on weekdays (\(\bar{x} = 413\)) than weekends (\(\bar{x} = 411\)). TABLE 8 shows the results from the analysis. FIGURE 19 shows a graph of the hourly differences between weekend and weekday in CO₂ concentrations obtained by the GSU LICOR station.

![Licor 1 minute CO₂ Concentrations DJF](image)

FIGURE 18 Histogram of the LICOR CO₂ dataset for DJF 2010
TABLE 8 Results from the Student’s \( t \) Test comparing difference in the means between weekends and weekdays at the LICOR station.

<table>
<thead>
<tr>
<th>Group</th>
<th>N</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>Std. Error Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO2Hour 1 (Weekend)</td>
<td>624</td>
<td>411.184841</td>
<td>15.8706648</td>
<td>.6353351</td>
</tr>
<tr>
<td>CO2Hour 2 (Weekday)</td>
<td>1536</td>
<td>413.450261</td>
<td>14.7678857</td>
<td>.3768103</td>
</tr>
</tbody>
</table>

Levene's Test for Equality of Variances

<table>
<thead>
<tr>
<th></th>
<th>F</th>
<th>Sig.</th>
<th>df</th>
<th>Mean Difference</th>
<th>Std. Error Difference</th>
<th>95% Confidence Interval of the Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equal variances assumed</td>
<td>0.19</td>
<td>0.890</td>
<td>2158</td>
<td>-3.611</td>
<td>0.2654197</td>
<td>-3.706586 - 3.484858</td>
</tr>
<tr>
<td>Equal variances not assumed</td>
<td>0.067</td>
<td>1083.938</td>
<td>0.02</td>
<td>-2.2654197</td>
<td>0.7386722</td>
<td>-3.7148090 - 3.7160304</td>
</tr>
</tbody>
</table>

Student's \( t \) Test Group Statistics
Buffered stations north and northeast of the GSU station had the highest CO$_2$ concentrations while the southern and western stations had the lowest. The buffered stations for Atlanta resulted in the highest CO$_2$ concentrations as much as 193 ppm lower than Idso’s (2001) highest measurements across Phoenix, Arizona. Additionally, in contrast to Phoenix, a predominant northwest to easterly airflow during midday may have brought with it higher CO$_2$ concentrations from other regions to the north and east of Atlanta. For Atlanta, from midnight to 9:52 am, 310-360° winds occurred at an average speed of 3.6 meters per second. In Atlanta, approximately one hour before observation measurements began until the measurements were completed, the winds had shifted from between 40 and 100° with average wind speed of 4 mps. Notwithstanding, these facts fail to explain the northern to northeastern higher accumulations of
CO$_2$ or the southern stations lowest. The resulting assumption is that localized accumulations of CO$_2$ concentrations occur from the spatial structures of intense human activity (Wentz, Gober et al. 2002).

During the study day, CO$_2$ concentrations values obtained in Atlanta were lower than other studies performed at other metropolitan areas (Henninger and Kuttler 2010). The transect across the buffered stations produced the highest CO$_2$ mean of 457 and 451ppm at station 4 and 1, respectively, at 12% above the GSU station at their respective times. Station 4, just south of North Atlanta and north of North Druid Hills, located less than 1km north and east of the Northeast Expressway I-85 and adjacent to Clairmont Rd., is located in a heavily urbanized residential area. Although the average speed of the mobile unit used in obtaining the mobile CO$_2$ transects at sample stations was calculated to be at 37kph (23mph) for the duration within station 4’s buffer zone, it may be likely that much of the CO$_2$ concentration measured in this area is due to the exhaust from the mobile unit and/or other vehicles in close proximity. A Google image of the area is presented in FIGURE 20.
Station 1, Northeast of Chamblee, had the second highest concentrations of CO\textsubscript{2}. At an average of 454ppm CO\textsubscript{2}, this station may have been under the influence of heavy vehicular traffic and traffic lights which halted the mobile unit along with other nearby automobiles. At an average rate of speed of 40kph, the mobile unit may have influenced the observed ambient CO\textsubscript{2}. FIGURE 21 shows a Google image of the area in proximity to station 1.
Stations 3, 6, and 7 were averaged to contain 453, 450, and 445 ppm, respectively, of ambient CO$_2$ within each buffer zone during the study day. Stations 3 and 6 are located north of the GSU station and are located in heavily urbanized areas and are located closer to the “core” of Atlanta than stations 1 and 4. Station 3 was approached by traveling east on West Paces Ferry Road approximately 4.5 kilometers, turning left onto Valley Road into a mixed-use residential neighborhood, and is one kilometer west of Buckhead. It may be seen in FIGURE 22.
Station 6 was located near the intersection of Peachtree St. and 14th St. in Northeast Atlanta. The mobile unit approached Station 6 from the north after crossing over the Northeast Expressway. The CO$_2$ measured within the buffer zone here may have been heavily influenced by traffic stops, public transportation, and heavy vehicular traffic. An image of the area surrounding Station 6 is provided in FIGURE 23.
Station 7 consisted of traveling Southwest on North Decatur Road from State Route 29 continuing past Clairmont Avenue approximately 700 meters. Although the centroid of station 7 is situated within a populated residential area with single family dwellings, it is in close proximity to urban structures such as Emory University’s campus, the city of North Decatur, and is less than 2km Northwest of Fernbank Forest and Recreation Center. The speed of the mobile
unit while within the buffer zone of sample station 7 was calculated to be an average of 41kph. A Google image of the area surrounding station 7 may be seen in FIGURE 24.

The lowest of the sampling stations was located in the southwest portion of the study area. Station 13 contained the lowest ambient CO$_2$ concentrations of all the buffered sample stations. As may be seen in FIGURE 25, the land-use in the area is predominantly residential.
Surprisingly, this station is within less than 3 km and to the northwest of Hartsfield-Jackson Airport, a known source emitter of carbon dioxide.

FIGURE 25 Station 13 contained the lowest CO$_2$ concentrations of all the buffered sampling stations

In Phoenix, Arizona, Idso, Idso et al (2002) obtained one minute averages of near surface CO$_2$ concentrations that exhibited considerable scatter throughout the day, yielding extremes in maximum and minimum values that were not representative of mean maximum and minimum.
His research worked with 30 minute averages to develop plots of daily maximums and minimums. The CO$_2$ transect in Atlanta was similarly representative of those variations in CO$_2$ throughout the study area. As may be seen in FIGURE 11, many of the highest CO$_2$ concentrations occurred near buffered sample stations. Although many buffered sample stations did not contain the top 10 percentile of CO$_2$ as the red transects show, they were under the influence from the nearby higher CO$_2$ concentrations in the area. As mentioned earlier, winds were from anywhere between 310 to 100° at speeds between 3.6 to 4mps. In the case of the northern transect near station 3 and 4, influences on transect data from within the study area would have probably come from within the study area, however, the higher concentrations of CO$_2$ at the northernmost edge of the study area, i.e. stations 0 and 1, would have come from outside the study zone. In light of this, along with the possibility that higher traffic volumes may come from the northern most part of Atlanta, and with the winds from the northwest to east, it may be possible that CO$_2$ concentrations are normally highest during weekdays in the northern part of Atlanta.

Significant differences between CO$_2$ during all days in DJF and February the 9$^{th}$ at the GSU station may have been an anomaly; possible due to its departure from normalcy in temperature or other factors that are beyond the scope of this study. However, the weather archives from Peachtree Weather Center shows that February 9$^{th}$ had below normal temperatures of 9°F during the early morning hours. As may be seen in FIGURE 15, all hours of the day for the study day contained at minimum 5 ppm more than the averaged 90 period, however, during the hours between 12 and 14 of the study day, CO$_2$ concentrations at the LICOR station fell below the seasonal average for that time of day.
Analysis of the DJF 2010 data from the LICOR station at Georgia State University suggests that fossil fuel combustion from automobiles and transport vehicles may be one of the major sources of CO$_2$ in the Atlanta area. It has been shown that CO$_2$ levels peak in areas with intense human activity and decline where decreased activity exists (Berry and Colls 1990; Wentz, Gober et al. 2002). Although weekdays in Atlanta during the 2010 winter contained statistically higher ambient CO$_2$ concentrations than weekends, early morning weekend CO$_2$ was, on average, higher than weekdays by 7ppm, decreasing to 411ppm at 6am, increasing to 417 at 9am, only then weekdays exceeding weekends. The phenomena of higher early morning weekend carbon dioxide may be due, in part, to the Atlanta area’s weekend nightlife or from passersby traveling to other destinations via Atlanta’s major interstate system. Notwithstanding, weekend CO$_2$ concentrations soon after morning rush hours are quickly overtaken by the weekday concentrations, most likely due to heavy transport and suburban commuters inbound from peripheral areas.

7.0 CONCLUSION

In this study, transects were developed within urban Atlanta to explore the spatial variability of CO$_2$ along with a study of CO$_2$ temporal variability at Georgia State University during the 2010 winter season. This study was limited by temporal and spatial constraints and may not be entirely representative of the results found. Given the duration of data accumulation that was used in the study, it was found that CO$_2$ in Atlanta is highly erratic however, long term studies may prove otherwise. Data obtained in this study may be used for future analysis of the influence of vegetative sinks and atmospheric variability on CO$_2$ concentrations in the growing
season. Additional CO$_2$ concentration analysis would be beneficial for a more complete representation of Atlanta’s dynamics in other weather conditions and vegetative cover.

The ongoing debate concerning global warming is one that includes the inspection of both the international community as well as the local. At the local scale, models for CO$_2$ and other pollutants in the urban environment can be produced that would enable policy makers to make decisions that produce results that are beneficial to the growing demands of the urban environment. On the global scale, models of atmospheric pollutions can help international policy makers construct informed decisions about the fate of the world. The importance of an ongoing monitoring system for atmospheric pollutants in an urban environment is undisputable for both local and global inhabitants.
REFERENCES


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