AEROSOLS AND ASSOCIATED PRECIPITATION PATTERNS IN ATLANTA

by

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(Under the Direction of Thomas L. Mote)

ABSTRACT

The role of aerosol concentrations on summer precipitation was examined in Atlanta, GA, for 2003-04. Thursday had the highest average 2.5 µm particulate matter (PM 2.5) concentrations at two of three Environmental Protection Agency stations. Monday and Thursday had the largest area of significantly different precipitation when compared to other days of the week. All but the southeast quadrant of the metropolitan area had a significant difference in precipitation on high versus low aerosol days. High aerosol days had greater instability (higher average convective available potential energy and lower convective inhibition), and a slightly shallower mixing layer when compared to low aerosol days. Most of metropolitan Atlanta had higher precipitation amounts on high aerosol days and was significantly different from low aerosol days.

INDEX WORDS: Aerosols, Particulate Matter, Precipitation, Atlanta

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B.S., Northern Illinois University, 2005

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

2007

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August 2007

ACKNOWLEDGEMENTS

This thesis would not have been possible without the support of my family, friends, and colleagues. First and foremost, I would like to express my gratitude for my advisor Dr. Tom Mote. I am thankful for his guidance, insight, and patience throughout the process. I would like to thank my other committee members Dr. Andrew Grundstein and Dr. Marshall Shepherd for their continuing support that has encouraged my work. My committee's relentless assistance helped in getting past any bumps in the road along the way. I would like to thank my fellow colleagues at UGA. The support and extracurricular outlets they provided kept me level-headed. I especially would like to thank my fellow lab cohorts, Josh Durkee and John Frye, for helping me with every step of the process and providing many comical deviations from the daily grind. Finally, I would like to thank my family. Their unending support and constant encouragement of my work makes me realize how truly fortunate I am.

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CHAPTER 1

INTRODUCTION

Urban areas are considered to be local in scale, yet human influences in these areas can affect the environment at the local and global scales by changing the atmospheric composition and dynamics of the atmosphere. An increasing urban population is coupled with an increasing use of local urban and industrial energy and thus leads to a greater release of heat, moisture, and aerosols into the atmosphere from the urban area.

Howard (1833) first documented a temperature difference between London and the surrounding rural area. This temperature difference would later be named the "urban heat island" (UHI) by Manley (1958) (Figure 1.1). The UHI exists for several reasons. The boundary layer in urban areas is modified into the UHI because the artificial surface has different thermal properties than natural surfaces (Shepherd 2005). Moreover, Oke (1987) explained that the UHI reduces cooling during the afternoon and evening because of the reduced sky-view due to buildings. This reduced sky-view means buildings face other warm building surfaces, more than open space, reducing the amount of radiative loss of heat. Other possible factors that contribute to the UHI include reduced evapotranspiration, anthropogenic heating, and radiative effects of aerosols (Oke et al. 1991; Diem and Brown 2003; Shepherd 2005).

The UHI can also exacerbate heat-related health problems. People living in urban areas are the most susceptible to heat-related health concerns (Patz et al. 2000). The UHI at night is greater during intense hot spells (Changnon et al. 1996). When heat-related deaths are compared

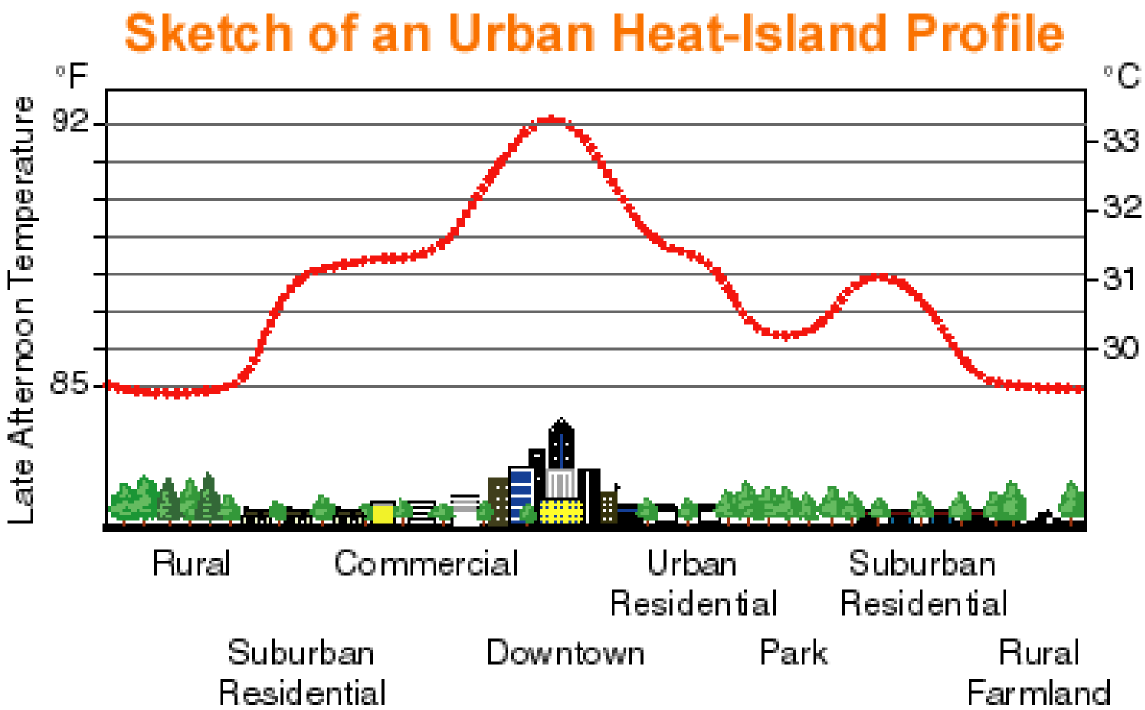


Figure 1.1. This sketch of an UHI profile indicates warmer temperatures over the urban region when compared to the surrounding rural area. From Lawrence Berkeley National Lab (2006).

to other weather events in the United States, including hurricanes, tornadoes, flooding, and lightning, they cause significantly more loss of life than the others (Table 1.1). During one extreme heat wave event during July 1995 in Chicago, 525 people died from the heat (Changnon et al. 1996).

Increased temperatures are also associated with increased particulate matter (PM) concentrations. Fischer et al. (2004) found that hot weather, either acting alone or with photochemical and particulate air pollution, could be contributing to a large number of deaths that have been attributed solely to heat. Other work has suggested that high temperatures and air pollution concentrations could interact to create a larger effect than each factor acting alone (Katsouyanni et al. 1993).

One way heat and pollution concentrations from urban areas are important is that they

Table 1.1. 10 year average (1997-2006) number of deaths attributed to weather in the United States. From National Weather Service (2007).

Condition	10 Year Average
Flood	74
Lightning	44
Tornado	62
Hurricane	117
Heat	170
Cold	18
Winter Storm	41
Wind	47

Table 1.2. Projections of the extent and direction of potential health impacts of climate variability in urban areas. From Patz et al. (2000).

Potential heath impacts	Weather factors of interest	Direction of possible change in health impact
Heat-related illnesses and deaths	Extreme heat and stagnant air masses	Increase
Extreme weather events related health effects	Precipitation variability (heavy rainfall events)	Increase
Air pollution-related health effects	Temperature Stagnant air masses	Increase

could have an effect on precipitation processes, either enhancing or suppressing amounts. Heavy rainfall events might also lead to flooding, that can in turn lead to deaths in highly populated areas. Table 1.2 is an assessment of projected health impacts for urban areas (Patz et al. 2000). Potential health impacts, including heat, extreme weather events, and air pollution, due to higher temperatures, stagnant air masses, and heavy rainfall events are expected to rise as urban areas expand.

1.1 Precipitation and the Urban Environment

Urban areas may influence precipitation patterns that possibly could lead to flooding. The Metropolitan Meteorological Experiment (METROMEX) observed urban influences on precipitation patterns in the 1970s. The scientists involved in METROMEX found higher precipitation amounts downwind of the urban area. More recent studies found an enhancement of precipitation downwind of urban areas (Craig and Bornstein 2002; Shepherd et al. 2002; Diem and Brown 2003; Rozoff et al. 2003; Molders and Olsen 2004; Diem and Mote 2005). Other work has shown aerosols in urban environments inhibit precipitation formation (Rosenfeld 2000) or have no effect on precipitation formation (Thomas 1971; Lowry and Probáld 1978).

Anthropogenic activities have been observed to have an effect on local atmospheric processes. Research has found pollution to inhibit precipitation processes within clouds (Rosenfeld 2000; Ramanathan et al. 2001; Kaufman et al. 2005). However, other research found delayed precipitation formation in polluted clouds (Andrae et al. 2004; Lin et al. 2006). Some research has found pollution concentrations peak during the week (Cerveny and Balling 1998; Husar and Husar 1998; Cerveny and Coakley 2002). Analysis of precipitation and pollution over cities along the east coast United States found no weekly cycle in rainfall (DeLisi et al. 2002). However, rainfall was found to peak during weekdays in the Southeast United States, when aerosol concentrations were the greatest (Bell et al. 2007).

Although the literature continues to indicate that the urban environment has left its signature on local precipitation patterns, skeptics remain. There is no definitive answer if a weekly cycle of pollution in an urban environment affects precipitation amounts and spatial patterns. There are questions still to be answered:

- Have aerosol concentrations enhanced, inhibited, or had no effect on convective storms?
- Have rainfall amounts been altered by urban aerosols? If yes, where in relation to the urban area?
- What role has pollution played in the microphysical processes in clouds over urban and surrounding rural areas?

This study attempts to address a few of the previous questions using the city of Atlanta, GA, as a case study. Atlanta, GA, was used as a study site because of previous research demonstrating urban-initiated rainfall (Bornstein and Lin 2000; Dixon and Mote 2003; Diem and Mote 2005) and possible connections between pollution and precipitation processes (Bell et al. 2007). The summer months of June, July, and August for 2003-04 were analyzed.

Three Environmental Protection Agency (EPA) recording stations in the metro area, two in DeKalb County and one in Fulton County, were used to see if there was any weekly cycle in 2.5 μm particulate matter (PM 2.5) concentrations. National Weather Service WSR-88D radar data from the Peachtree City, GA, (KFFC) were used to observe if any weekly cycle in mean precipitation amounts occurred over the metro-Atlanta area using the Digital Precipitation Array (DPA). Days with a persistent maritime tropical (MT) air mass present in Atlanta were used when analyzing pollution concentrations and rainfall amounts. Days with MT air present meant forcing on the local atmosphere was most likely due to mesoscale forcing (e.g., urban region) and not other large-scale forcing mechanisms (i.e., fronts). A statistical analysis confirmed if any cycles of pollution and precipitation existed. The concentration frequencies of days classified as high and low aerosol days were examined against precipitation to see if there was any significant difference between the two frequencies. This research should provide a better understanding of the role aerosols play on urban precipitation patterns. It also should help to improve forecasting and researching these patterns and in determining new ways to interpret the urban effect on the local atmosphere.

CHAPTER 2

BACKGROUND

2.1. Early Urban Effect Research

As early as the 1920s, scientists found that the urban area had an effect on precipitation amounts and distribution. Horton (1921) noted that some cities seemed to spawn thunderstorm development. On days when there were no thunderstorms outside of Albany, NY and Providence, RI, he observed that some thunderstorms originated over the city and did not travel far past the urban area. Kratzer (1937) found that higher rainfall amounts occurred east of the city of Munich than west of the city and higher amounts in the city than in the country, especially in the summer.

Atmospheric scientists have attempted to expand those earlier findings by doing comparative studies of cities to gauge their influence on precipitation processes. Huff and Changnon (1972) studied the city of St. Louis by observing the frequency of days with rainfall amounts $\geq$ 6.35 mm. The areas directly downwind of the city's center produced more precipitation events than those in the rural areas during each of the five weekdays. There were no differences between the areas on either weekend day. The "Eight Cities Study" by Huff and Changnon (1973) merged the analyses of the precipitation climatologies of individual cities. Stout (1962) studied La Porte, IN, and found the city to have increasingly greater precipitation amounts as surrounding areas observed lesser precipitation amounts. Stout attributed this to "cloud seeding" from aerosols produced by the expanding industrial areas east of Chicago. Changnon (1968) coined the unexpected increase of precipitation observed in La Porte as the "La Porte Anomaly".

A collective research effort was carried out in the 1970s to observe precipitation patterns in urban areas, called the Metropolitan Meteorological Experiment (METROMEX) (Lowry 1974). It was a response to the need for both theoretical and observational information in order to answer questions about the "La Porte Anomaly" and related findings (Stout 1962; Changnon 1968). The METROMEX scientists (Diab 1978; Braham 1981; Braham et al. 1981) found that cloud bases were typically higher over the urban area than in the surrounding rural areas on a typical summer day. There appeared to be a moisture deficit over the urban area coupled with higher mixing depths and the presence of giant cloud condensation nuclei in the updrafts. This led to higher rainfall amounts several tens of kilometers east of the urban area. They believed the clouds over urban areas were more likely to merge with other cloud systems to produce stronger storms and urban clouds were more likely to enter a mid-level tropospheric unstable layer than clouds over rural areas.

There has been much debate over the effect of urban areas on precipitation processes. The possible urban mechanisms affecting precipitation include: (1) bifurcation of moving thunderstorms around a city due to a barrier divergence effect (e.g., Bornstein and LeRoy 1990; Bornstein and Lin 2000), (2) increased amounts of pollution-derived cloud condensation nuclei (CCN) (e.g., Diem and Brown 2003; Molders and Olson 2004), (3) enhancement of convergence due to increased surface roughness (e.g., Changnon 1981; Bornstein and Lin 2000), and (4) boundary layer changes that lead to downstream movement of UHI-generated convective clouds (e.g., Shepherd et al. 2002; Diem and Mote 2005).

2.2. Urban Precipitation Enhancement

Many recent studies have tried to validate and expand the research from METROMEX and post-METROMEX investigations. Some studies have shown that there is an enhancement of precipitation within cities when compared to the surrounding rural areas. Changnon (1969) found the cities of Chicago, IL, Champaign-Urbana, IL, and Tulsa, OK, had warm season precipitation totals that were 4-6% higher in urban areas when compared to rural areas. A study of Detroit, MI, found that the city received 20% more precipitation in the summer compared to the surrounding rural areas, yet received less precipitation than rural areas during the autumn and winter (Sanderson et al. 1973). Stulov (1993) studied the monthly precipitation totals from 25 summers for Moscow, Russia. This study found that when an unstable and moist air mass moved through the city, the urban area initiated the formation of cells that produced rain within the city, as well as in the lee of the city. Jáuregui and Romales (1996) found that Mexico City, Mexico, showed a significant increasing trend in urban effect as the city grew. The UHI seemed to correlate with the intensification of rainfall during the wet season (May-October). Rainfall in the rural area, upwind of the city, was unaffected by the urbanization.

More recent studies have found an enhancement of precipitation directly downwind of the city due to anthropogenic activities. Rozoff et al. (2003) found that surface convergence on the eastern side of St. Louis played a role in the initiation of convection downwind of the city. Molders and Olson (2004) stated that precipitation enhancement was found over and downwind of Fairbanks, AK. Diem and Brown (2003) and Shepherd (2006) showed that the city of Phoenix positively affected summer precipitation downwind of the city. A recent study by Niyogi et al. (2006) simulated a mesoscale event in Oklahoma City, OK, that showed the impact of surface vegetation patterns on the atmosphere. Their land surface model included an urban canopy model, which took into account anthropogenic heat sources within the urban area. The model showed that the urban area concentrated the precipitation downwind of the downtown region. The model results were supported by a case study they conducted.

Model simulations by Craig and Bornstein (2002) found that urban-induced convective events developed on the eastern edge of Atlanta. The work by Craig and Bornstein was supported by Shepherd et al. (2002) in which they found that during the warm seasons of 1998-2000, there was a 19.5% increase in rainfall rates downwind of the Atlanta metropolitan area when compared with an upwind control area (Figure 2.2.1). Bornstein and Lin (2000) found that storms initiated in Atlanta UHI-induced convergence zones during the daytime and precipitation areas propagated upwind (Figure 2.2.2). These results were also found in the METROMEX data (Changnon 1981) and in New York City (Bornstein and LeRoy 1990). A caveat to the research by Shepherd et al. (2002) was that is was conducted over a limited time period for Atlanta and used a fairly coarse-resolution satellite-based dataset. However, more recent climatological work by Diem and Mote (2005) provided a longer term analysis. Their work found a northeast and downwind anomaly from Atlanta with precipitation amounts that may have been enhanced by urban effects. They suggested one effect was an increase in the depth of the urban planetary boundary layer that becomes conductive to cloud merging and thunderstorm amplification. This result is supported by modeling results in Shepherd (2005) and Rozoff et al. (2003) who both found an elevated boundary layer over Houston and St. Louis, respectively. Atlanta UHI-initiated convection appears more frequently under the most humid air masses, rather than with the greatest UHI intensities (Dixon and Mote 2003).

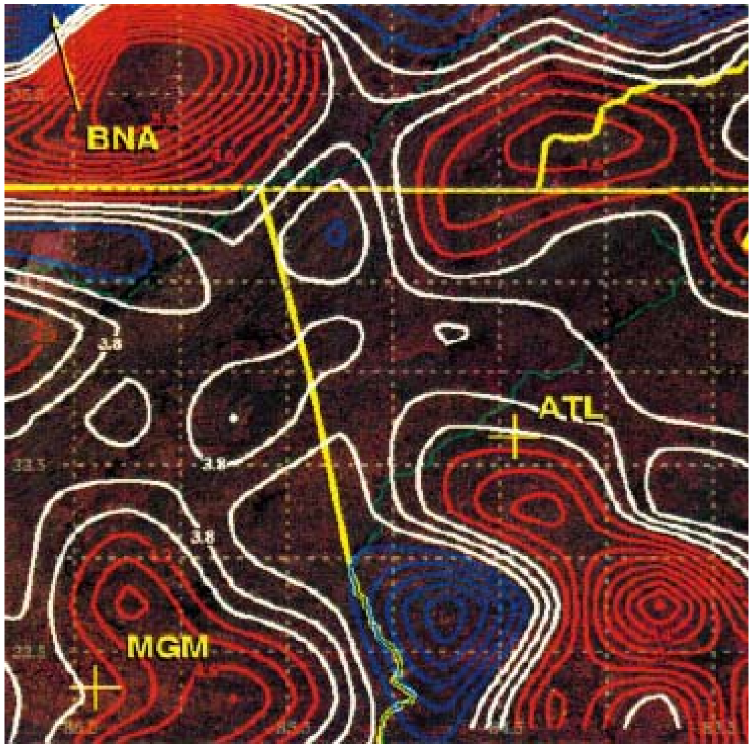


Figure 2.2.1. Contour plot of warm-season mean rainfall rates for 1998-2000. Red contours are areas of at least 4.4 mm h^{-1} and blue contours are less than or equal to 3.6 mm h^{-1}. From Shepherd et al. (2002).

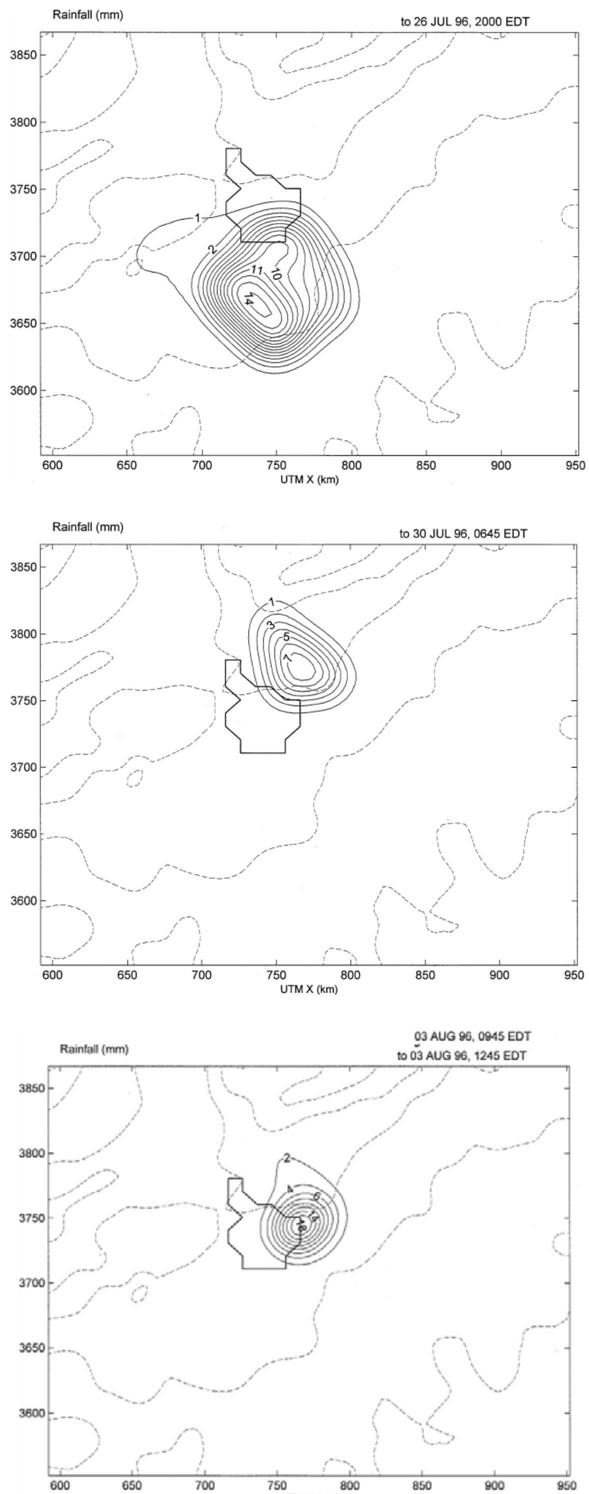


Figure 2.2.2. Precipitation contours (mm) for the Atlanta area for 26 July, 30 July, and 03 August 1996. From Craig and Bornstein (2002).

Most of these studies regarding precipitation enhancement suggest that the differences between urban and rural land characteristics, coupled with the formation of mesoscale boundaries near urban areas, may lead to feedbacks within the atmosphere. This urban-rural land contrast could become a prime area for convection, pre-existing or initiated, that typically occurs downwind of a city (Niyogi et al. 2006).

2.3 Contraindications of an Urban Effect on Precipitation

A leading study demonstrating that pollution from urban areas actually suppresses precipitation looked at clouds ingested with pollution in cities in Turkey, Canada, and South Australia to see if they had an effect on precipitation (Rosenfeld 2000). Vertical cross sections showed that the pollution infested clouds had no differences in cloud top heights in and outside the areas of suppressed precipitation. The clouds were found to have both ice precipitation formation and cloud droplet coalescence inhibited.

On the other hand, studies have shown that urban areas have no effect on precipitation patterns. Thomas (1971) reported that the city of Toronto had no effect on precipitation amounts. A study on the Hungarian city of Dunaujváros found that the urban and industrial build up of the city had no statistically significant effect on rainfall amounts (Lowry and Probáld 1978). These contradictions illustrate how little is still known about the characteristics of cities that may affect precipitation and what physical processes are contributing such effects.

2.4 Aerosol Influence on Precipitation Processes

Particulate matter consists of condensed liquids, fine liquid droplets, or solid particles absorbed onto solid particles. Airborne particulates are a mixture of several different air pollutants. Primary sources of particular matter are from combustion, incineration, mining, construction, motor vehicle exhaust, forest fires, ocean spray, and volcanic activity. Individually these particles are invisible to the naked eye, but are collectively seen as clouds or a fog-like haze (Georgia Department of Natural Resources 2006).

The residence times of aerosols in the atmosphere are dependant on size. Radii of 10 μm reside for about half a day and those with a radius of 1 μm reside in the atmosphere for about a month (Lyons and Scott 1990). Oke (1987) states that there are three processes that remove pollutants from the atmosphere: gravitational settling, dry deposition, and precipitation scavenging. Gravitational settling occurs when particulate matter greater than 1 μm and particles larger than 10 μm settle out very close to the emission source. Dry deposition involves an underlying surface that acts as a pollution sink that creates a downward flux of pollution. Precipitation scavenging entails the processes of collision/coalescence and the Bergeron process where pollutants are removed in falling precipitation. An even more effective method of precipitation scavenging is when precipitation below the cloud sweeps up the material through which it falls.

Aerosols are typically concentrated near their source region (Toon 2000), so they would most likely have the greatest effect on atmospheric processes near urban areas. Brock (1972) said natural and anthropogenic material in the atmosphere make up about 75% of the total of aerosol with sources such as sea spray (40%), wind-generated dust (20%), forest fires (10%), and combustion and other industrial operations (5%). The conversion of gaseous components of the atmosphere into small particles by photochemical and other chemical processes makes up the remaining 25%.

Clouds are the intermediate step in converting atmospheric water vapor to precipitation. Precipitation may be initiated by means of the ice-crystal or coalescence process, with coalescence favored in warm clouds with high liquid water contents. Rain can develop in warm clouds of the cumulus type in as short of a time as 15 minutes after cloud formation. This development is due to gravitational coalescence among the droplets. Droplet populations most likely to produce rain in a short time are those with a broad spectrum with a high rate of collisions. An impediment to this coalescence process is that small droplets have small collection efficiencies (Rogers and Yau 1989).

Rosenfeld's (2000) study stated that the lack of precipitation in the nonprecipitating clouds was not because there was a lack of cloud water. He found that there was little growth in effective radius with decreasing temperatures within the pollution plumes and thus prevented the formation of ice particles in clouds. This indicated a lack of coalescence and inhibited precipitation. An explanation is that pollution reduces the radius of the largest cloud droplets below the threshold value for ice generation in clouds.

An increase in the number of cloud condensation nuclei (CCN) may have a considerable impact on the microphysics of clouds (Albrecht 1989). Clouds tend to have more numerous small droplets in a polluted environment and therefore may lead to a suppression of precipitation (Kaufman et al. 2005). Twomey (1977) explained that increasing amounts of pollution lead to increasing cloud nucleus concentrations. This in turn increases the number of cloud droplets and cloud optical thickness. Smaller droplets reduce the efficiency of droplet growth by collision coalescence, which at least under some conditions reduce precipitation formation and increase cloud lifetime. Human-made aerosols also produce brighter clouds that are less efficient at releasing precipitation and can lead to a reduced hydrological cycle (Kaufman et al. 2005). Ramanathan et al. (2001) explain that increases in aerosol amounts led to an increase in droplet concentrations, and thus decreases mean droplet radius. The amplified concentration of droplets should result in a decrease in precipitation efficiency that leads to a suppression of precipitation in polluted clouds.

A typical cloud droplet developed from water vapor is about 10 μm in radius. About 10^6 cloud droplets must collide and coalesce in order to make a precipitation-sized drop (Toon 2000). The droplets in an unperturbed cloud collect up to about 64 times the volume of air than the ones in the polluted cloud (Toon 2000). Aerosols affect clouds by creating eight times as many droplets, half the size, twice the optical depth and surface area, and with a higher reflectivity than a natural cloud (Figure 2.4.1). However, it is possible that pollution could contain giant soluble particles that could initiate precipitation (Toon 2000).

Andreae et al. (2004) found that convective clouds that formed in smoky air over the Amazon led to reduced droplet size with increased CCN concentrations which suppressed the onset of warm rain processes. Similar findings were discovered relating CCN concentrations and warm rain development by van den Heever and Cotton (2005) for St. Louis. On the other hand, Andrae et al. (2004) also found that the delay in precipitation led to larger cloud heights with vigorous convection that created intense thunderstorms and hail. This work was later confirmed by Lin et al. (2006) by concluding that increasing the amount of aerosols in the atmosphere led to increased precipitation, increased number of intense rainfall events, and greater ice formation.

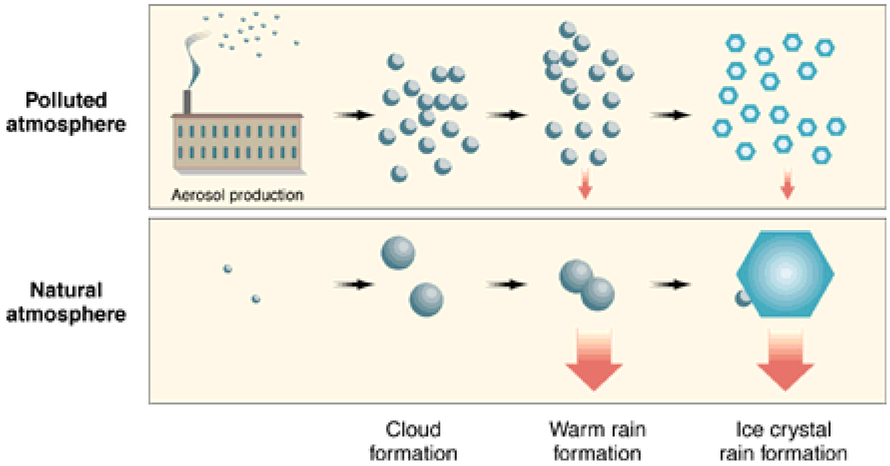


Figure 2.4.1. Process by which aerosols affect clouds. From Toon (2000).

Jin et al. (2005) suggested that rainfall is less directly affected by aerosols than clouds. They found little annual seasonality in rainfall over Houston and New York City in their study. They did find that increased cloud effective radii for water clouds led to increased rainfall amounts, but no relationship was found between rainfall amounts and effective radius in ice clouds. New York City was found to have a peak in aerosol optical thickness and water cloud effective radius on Wednesdays and liquid water path peaking on weekends. They attribute the weekly cloud cycles to be a human footprint on the local atmosphere. Other research has found there to be a weekly cycle in pollution in which the highest levels occur during the week with the lowest levels appearing on the weekends (Cerveny and Balling 1998; Husar and Husar 1998; Cerveny and Coakley 2002).

2.5 Weekly Cycle of Precipitation

Little research has been done to see if this weekly cycle in pollution has led to a weekly cycle in rainfall. One study looked at seven United States east coast cities (Washington, D.C. to Portland, Maine) to establish if there was a weekly cycle in rainfall amount or frequency at any or all of the sites resulting from anthropogenic influences (DeLisi et al. 2001). While some of the intensity and frequency results suggested a preference for one day of the week, there was no statistically significant weekly cycle. This study concluded that if a weekly cycle exists, it is too subtle to identify from the 20-year data record used.

Other research has found a weekly cycle of summer storms over Japan and the United States. Research by Sato and Takahashi (2000) utilized the Automated Meteorological Data Acquisition System (AMeDAS) data from the Japan Meteorological Agency to analyze heavy rainfall rates (>10 mm/hr). They examined Otemachi, located in central Tokyo, in the month of August for 1976-1998. The study assumed there were convective storms producing the precipitation. An increase appeared to occur during the weekdays. They suggest that analyses are needed on the weekly cycles of air pollution, such as aerosols, in order to support the reasoning for the weekday precipitation enhancement.

Bell et al. (2007) utilized the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager to look at summer (June, July, and August) precipitation for 1998-2005. In the Southeast United States, average rain rates peaked during the middle of the week (Tuesday-Thursday) (Figure 2.5.1). On the other hand, the nearby Atlantic Ocean and Gulf of Mexico showed the opposite occurring with rain rates highest on the weekends (Figure 2.5.2). Cerveny and Balling 1998 had similar findings off the United States east coast. The Bell et al. (2007) study found the entire Southeast United States to have a peak in rainfall on Wednesday (p-value of 0.1). A bootstrap statistical test showed that the variations in precipitation were unlikely to be due to other weekly variations in human influence or aerosol radiative heating or cooling of the

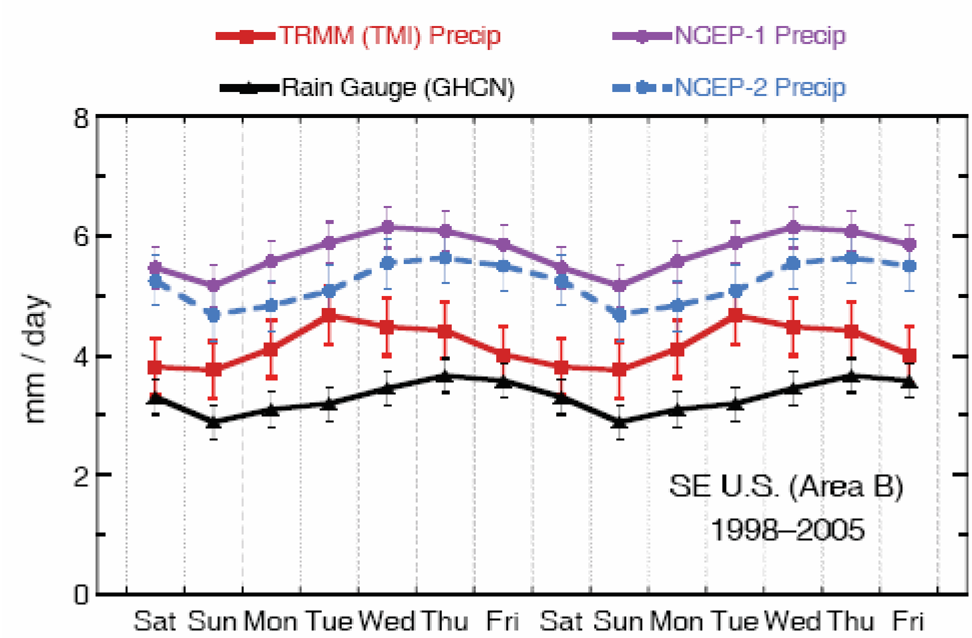


Figure 2.5.1. Averaged rainfall for the Southeast United States from Global Historical Climate Network rain gauges, National Centers for Environmental Prediction reanalyses versions 1 and R-2, and the TRMM Microwave Imager for each day of the week. From Bell et al. (2007).

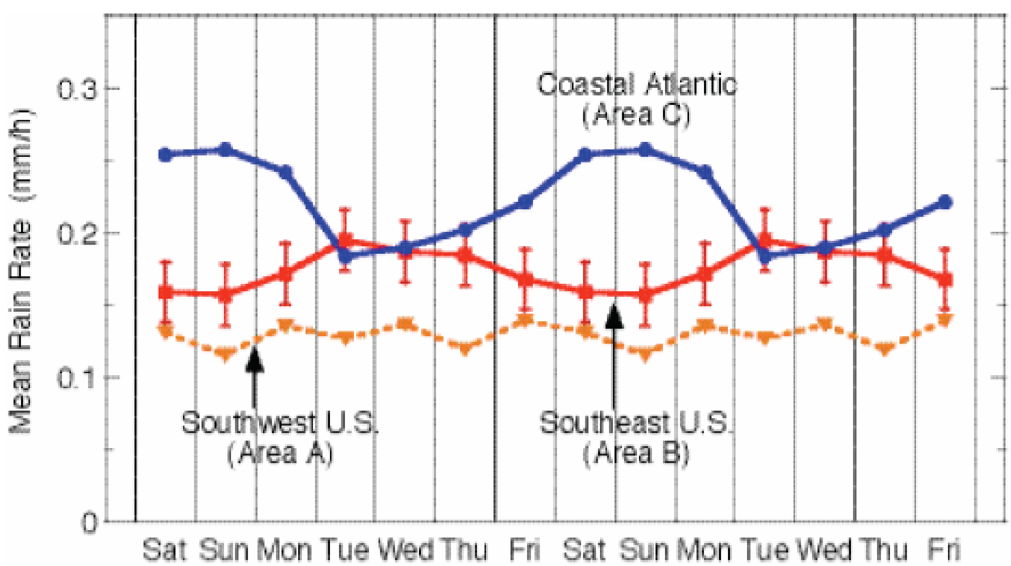


Figure 2.5.2. Weekly cycle in large-area averages of TRMM rainfall for three regions in the United States: Coastal Atlantic, Southeast, and Southwest. From Bell et al. (2007).

atmosphere, but only to a weekday peak in pollution. When Bell et al. (2007) examined a weekly cycle of afternoon rain, they discovered seven of eight years had a statistically significant increase in rainfall amounts on Tuesdays and Wednesdays (p-value of 0.0012). A caveat to this research was the use of the TRMM data, in which the temporal and spatial resolutions were relatively coarse and there were a limited number of rain gauges.

No study has yet to fully link the effect of pollution on observed weekly rainfall cycles. Rosenfeld's (1999, 2000) work has suggested that pollution aerosols suppress precipitation due to increases in CCN. However, Rosenfeld (1999) said the suppression of rainfall can enable unprecipitated water to reach elevated heights where freezing can release further latent heat and additionally strengthen cloud updrafts. If precipitation is delayed in this process, more water vapor can be ingested into the storm to further strengthen it (Andreae et al. 2004; Lin et al. 2006). Satellite observations have showed that clouds develop in areas of pollution tend to have greater heights (Koren et al. 2005).

2.6 Summary

Lowry (1998) created an extensive review of research that observed urban effects on precipitation amounts and provided recommendations for future work. It was stated that designed experiments with legitimate controls (i.e., stratification) are needed to test hypotheses with standard statistical methods. Lowry also said that experiments need to be reproduced in several urban areas, to avoid merging effects between different synoptic weather systems and to increase sample size by disaggregating standard climatic data, and in order to reflect the discontinuous nature of precipitating systems spatially small and temporally short experimental units are required. More recent analysis of past research by Shepherd (2005) has suggested that new observing systems are needed to monitor and track land use, aerosols, clouds, and precipitation. These systems can provide a more definitive understanding of the feedbacks and interactions with the urban area that can be implemented into modeling systems.

It has been nearly 40 years since the METROMEX scientists carried out such a large collective research effort. Even though they found a moisture deficit over the urban area and higher rainfall amounts east of the urban area, there is still much debate on the urban effect on precipitation processes. Recent studies have found precipitation to be enhanced directly downwind of the city due to anthropogenic activities (Diem and Brown 2003; Rozoff et al. 2003; Molders and Olsen 2004; Niyogi et al. 2006; Shepherd 2006).

Some research has focused on the influence of Atlanta, GA, on convective development. Atlanta UHI-induced convergence zones initiated daytime storms in work by Bornstein and Lin (2000). Convective events in previous studies were found to develop on the eastern edges of and downwind of Atlanta (Craig and Bornstein 2002; Shepherd et al. 2002; Diem and Mote 2005).

Studies analyzing the role of aerosols on precipitation processes have had contrasting results. Urban areas produce large amounts of pollution that increase the number of CCN in the atmosphere (Albrecht 1989). This decreases the mean droplet radius (Ramanathan et al. 2001) and creates a lack of coalescence and inhibits precipitation formation. However, delayed precipitation could lead to more dynamic convection with higher cloud heights producing increased precipitation amounts and events (Andrae et al. 2004; Lin et al. 2006).

Weekly peaks in pollution concentrations have been found during weekdays (Cerveny and Balling 1998; Husar and Husar 1998; Cerveny and Coakley 2002). However, little research has explored the idea that this pollution cycle could possibly lead to a weekly cycle in precipitation. DeLisi et al. (2002) found no statistically significant weekly cycle in rainfall intensity and frequency for seven U.S. east coast cities. Sato and Takahasi (2002) found an increase in precipitation during weekdays in Japan and say that analyses on pollution are needed to confirm any human footprint on rainfall patterns. Bell et al. (2007) found the southeast U.S. to have a peak in rainfall and pollution on Wednesdays, but did not directly relate the two. This thesis will directly relate the two.

CHAPTER 3

DATA AND METHODOLOGY

The principle objective of this study is to determine if there is a connection in the weekly cycles of pollution and precipitation in relation to the city of Atlanta, GA, during the summer season (June-August) for the summers of 2003-04. Atlanta (Figure 3.1) is an excellent study region because previous research has shown the city to initiate summer precipitation (Bornstein and Lin 2000; Dixon and Mote 2003; Diem and Mote 2005). In Atlanta's metropolitan statistical area (MSA), consisting of 20 counties, there was a population in 1950 of about 840,000 that grew to over 4,100,000 in 2000 (United States Census Bureau 2001). As a result of Atlanta's urban expansion, its UHI has most likely increased in size and created a larger influence on the local atmosphere. Radar-estimated precipitation amounts were analyzed for any urban influence on convection. In order to control for the effect of air mass type on precipitation, a synoptic classification was needed. Precipitation data was analyzed with pollution concentrations in order to establish any possible pattern (spatial or weekly) created by metropolitan Atlanta.

3.1 Data

3.1.1 Air Mass Type Data

In order to classify the synoptic environment for each day in the study's period of record, the spatial synoptic classification (SSC) was used (Sheridan 2007). SSC classifies seven

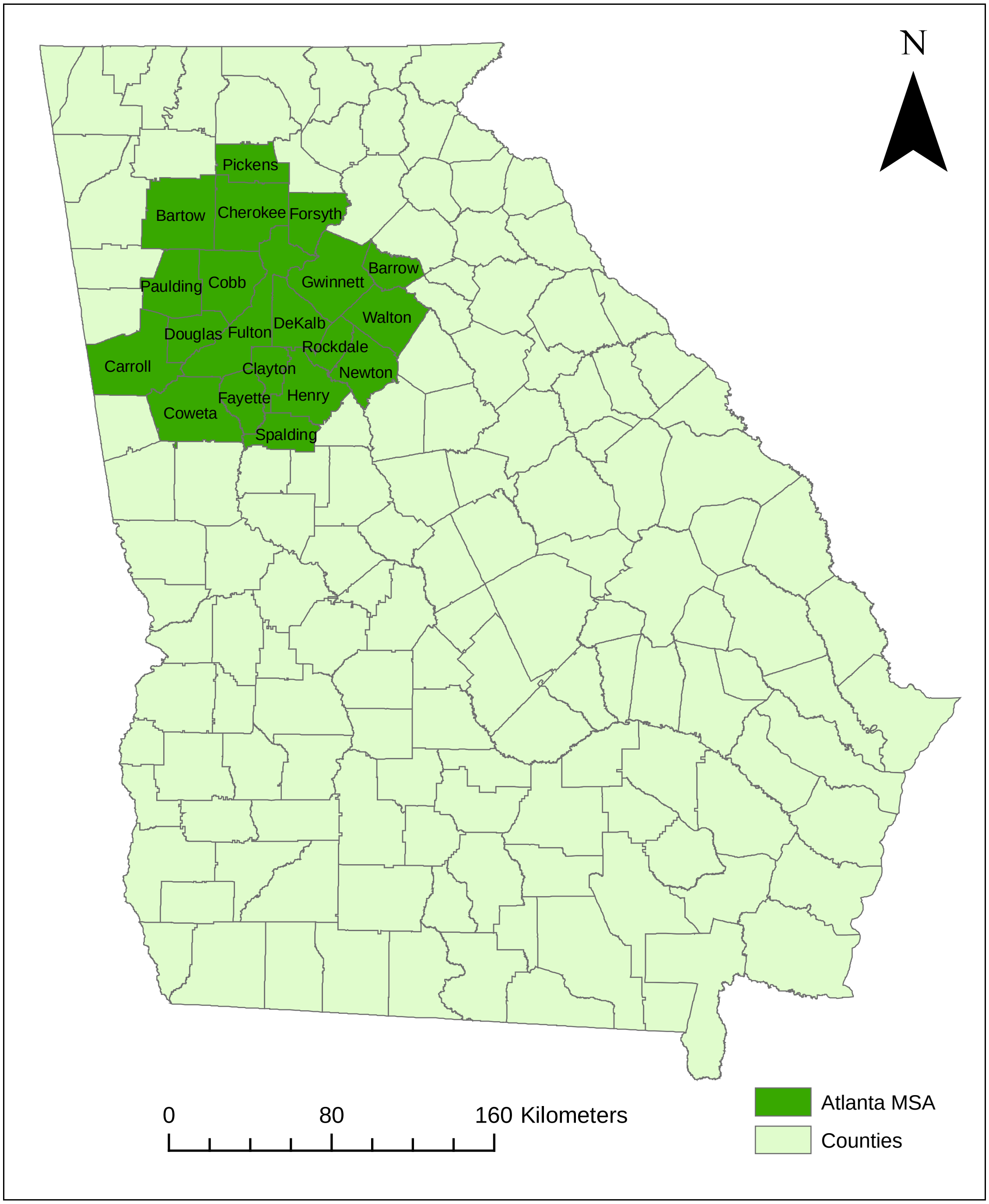


Figure 3.1. Map of Georgia counties with counties in Atlanta's 2000 metropolitan statistical area highlighted.

different weather types: dry polar (DP), dry moderate (DM), dry tropical (DT), moist polar (MP), moist moderate (MM), moist tropical (MT), and moist tropical plus (MT+). DP days are the coldest and driest. DM days are mild and dry, whereas DT days are the driest and hottest. The MP air mass signifies cool, humid, and cloudy conditions, while MM is significantly more humid and warmer than MP. The MT air mass is warm and very humid. The SSC does provide a subset of MT, named MT+, and is used for heat research by indicating days with the strongest MT air mass. Another category, transitional (TR), is applied to days during a period of transition from one air mass to another and may be indicative of frontal activity.

In order to establish air mass types, SSC selects seed days that contain typical surface meteorological characteristics of a certain air mass: temperature, dew point depression, mean cloud cover, mean sea level pressure, diurnal temperature range, and diurnal dew point range. A seed day is then used in a discriminant analysis to measure the separation among the different weather types with respect to multiple variables at the same time. This is then re-run with additional seed days till modification is no longer needed (Sheridan 2002).

Table 3.1.1 shows air mass frequency, average temperature and dew point for the months of June, July, and August. This information was obtained from the SSC and represents data from 1945-2006 for Atlanta (Sheridan 2007).

3.1.2 Aerosol Data

Aerosol data were obtained from the United States Environmental Protection Agency (EPA). The EPA's Ambient Air Monitoring Program (AMP) measures levels of air pollutants throughout the state of Georgia (Figure 3.1.1). The AMP is used to determine compliance with

Table 3.1.1. The frequency of days (%) each air mass was present in Atlanta, the average 1600 (LT) temperature (T in °C), and the average dew point temperature (T_d in °C) for the months of June, July, and August for 1945-2006 obtained from the SSC. From Sheridan 2007.

	June			July			August		
Air mass	**%**	**T**	**T_d**	**%**	**T**	**T_d**	**%**	**T**	**T_d**
DM	30.5	30.0	15.0	21.6	31.7	17.2	23.4	30.6	16.7
DP	4.6	25.6	11.7	1.4	26.7	14.4	1.1	26.7	13.9
DT	2.8	34.4	15.6	3.3	36.1	17.2	3.3	35.0	17.2
MM	20.2	25.0	20.0	28.8	26.7	21.1	22.3	26.1	20.6
MP	2.3	19.4	16.7	1.4	21.7	18.9	1.2	20.6	17.8
MT	30.4	29.4	19.4	34.1	30.6	20.6	40.8	30.6	20.6
MT+	3.1	32.8	20.6	2.9	33.9	21.7	2.2	33.9	21.1
TR	6.0	27.2	16.1	6.6	30.6	18.3	5.6	30.0	17.8

air standards established for five pollutants (ozone, sulfur dioxide, carbon monoxide, nitrogen dioxide, and particulate matter). Data from the Atlanta area stations from the AMP were used. Following previous research (Jin et al. 2005; Bell et al. 2007), this study analyzed 2.5 µm particulate matter (PM 2.5). PM 2.5 are fine particles that are less than or equal to 2.5 microns (µm) in diameter. They are composed of mostly secondary particles that form from emissions of power plants, industrial facilities, automobiles, and other types of combustion sources (United States Environmental Protection Agency 2007a).

The Georgia Department of Natural Resources (2006) has air samples taken over a period of 24 hours that are collected on Teflon filters with a PM 2.5 sampler that collects particles 2.5 microns in size and smaller. Before and after the sampling period, the filters are weighed in a laboratory to assess the amount of PM 2.5 in the air. Once this mass is found, it is divided by the total volume of the air sampled to give the mass concentration of the particles in the air. Another monitor draws air through a filter to analyze how the mass of the filter changes over the course of an hour. This monitor gives nearly continuous information on PM 2.5 (Georgia Department

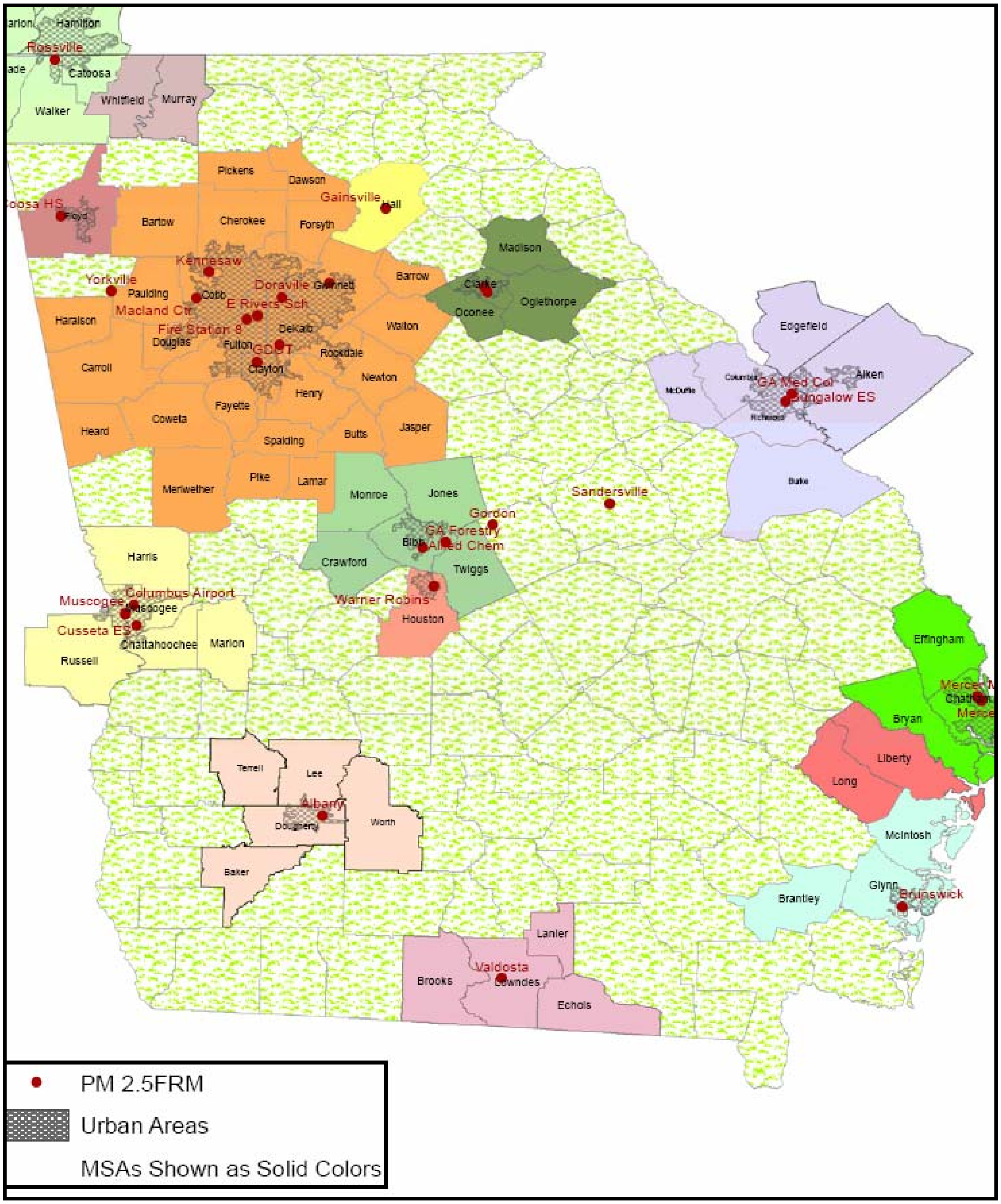


Figure 3.1.1. The location of Georgia's PM 2.5 monitors. From Georgia Department of Natural Resources (2006).

of Natural Resources 2006).

Daily average PM 2.5 concentrations were acquired for June, July, and August for 2003-04. Only three stations in the metro-Atlanta area had daily average PM 2.5 concentration data that aligned with the study's period of record (POR). The Doraville station (Monitor ID: 13-089-2001) is located in northern DeKalb County on the top of the Doraville Health Center building's roof. The Decatur station (Monitor ID: 13-089-0002) is a ground level station located in southern DeKalb County off of Wildcat Road. The Atlanta station (Monitor ID: 13-121-0032) is located in central Fulton County on top of the East Rivers School building on Battle Avenue.

All three stations are defined by the EPA as population exposure stations (United States Environmental Protection Agency 2007b). Population exposure stations are appropriate for measuring at the neighborhood and urban scales. (Electronic Code of Federal Regulation 2007) Table 3.1.2 describes the spatial scale criteria for PM 2.5. The PM 2.5 stations are expected to be associated with at least the neighborhood scale. This scale provides good information on trends because it represents conditions in areas where people regularly live and work. The neighborhood scale defines the concentrations of aerosols to be within some extended area of the city that has relatively homogeneous land use with dimensions in the range of 0.5 to 4.0 kilometers (Electronic Code of Federal Regulation 2007).

3.1.3 Precipitation Data

Austin (1987) stated that radar can measure, with sufficient accuracy, the aerial distribution of rainfall amounts. Because this thesis is concerned with summer-time storms, Austin (1987) further states that these rainfall events could be highly convective and radar may be the most reliable data source to obtain rainfall amounts. Radar estimates have been shown to

Table 3.1.2. Characteristics of the spatial scales associated with PM 2.5 measurements. From Electronic Code of Federal Regulation (2007).

Spatial Scale	Characteristics
Micro	This scale would typify areas such as downtown street canyons and traffic corridors where the general public would be exposed to maximum concentrations from mobile sources. In some circumstances, the microscale is appropriate for particulate sites; community-oriented SLAMS sites measured at the microscale level should, however, be limited to urban sites that are representative of long-term human exposure and of many such microenvironments in the area.
Middle	Measurements of this type would be appropriate for the evaluation of possible short-term exposure public health effects of particulate matter pollution. It would also be appropriate for evaluation of long-term or chronic effects. This scale also includes the characteristic concentrations for other areas with dimensions of a few hundred meters such as the parking lot and feeder streets associated with shopping centers, stadia, and office buildings.
Neighborhood	Measurements in this category would represent conditions throughout some reasonably homogeneous urban sub-region with dimensions of a few kilometers and of generally more regular shape than the middle scale. Homogeneity refers to the particulate matter concentrations, as well as the land use and land surface characteristics. Much of the $PM_{2.5}$ exposures are expected to be associated with this scale of measurement.
Urban	This class of measurement would be used to characterize the particulate matter concentration over an entire metropolitan or rural area. Such measurements would be useful for assessing trends in area-wide air quality, and hence, the effectiveness of large scale air pollution control strategies.
Regional	These measurements would characterize conditions over areas with dimensions of as much as hundreds of kilometers. Regional scale measurements would be most applicable to sparsely populated areas. Data characteristics of this scale would provide information about larger scale processes of particulate matter emissions, losses and transport.

provide better spatial representation of precipitation patterns when compared to regional precipitation networks with great density (Legates 2000). No other study that has studied pollution and precipitation cycles has ever employed the use of radar.

Precipitation data were obtained from the National Climatic Data Center (NCDC). The Next Generation Weather Radar system (NEXRAD) was utilized for this study. The NEXRAD system comprises of Weather Surveillance Radar-1988 Doppler (WSR-88D) sites throughout the United States (NCDC 2006). The NEXRAD site used in this study was the Peachtree City, GA (KFFC) radar site. Data for KFFC is available for 23 January 1995 up to the present. For this study, only radar data were obtained for June, July, and August for 2003-04.

The precipitation detection function (PDF) switches the radar's scanning mode from "clear air" to "precipitation" after the four lowest elevation sweeps (0.5º, 1.5º, 2.4º, 3.4º) show non-ground-clutter reflectivity echoes exceeding previously identified intensity and areal coverage thresholds (Fulton et al. 1998). In precipitation mode, the radar produces a volume scan approximately every six minutes, and thus provides samples of precipitation rate and depth about 10 times an hour to provide a very high spatial and temporal resolution (Vieux and Bedient 1998).

From the NEXRAD data, the Level III Digital Precipitation Array (DPA) product was used to extract estimated six-minute precipitation accumulations with a spatial resolution of approximately 4 km by 4 km (Legates 2000). Each volume scan of Level III products undergoes processing to eliminate ground clutter, account for radar beam blockage, and to check for outliers and spurious noise (Legates 2000). The term "digital" refers to products that maintain the original data resolution and can be utilized in quantitative processing algorithms outside of the WSR-88D scheme (Fulton et al. 1998).

DPA is an array format of estimated precipitation accumulations used to assess rainfall intensities (Kuligowski 1997; Fulton et al. 1998; NCDC 2006). Precipitation rates are not measured directly by radar, but rather backscattered energy obtained from precipitation particles in an elevated volume estimate that rate (National Oceanic and Atmospheric Administration 2005). Radar reflectivity (Z) is converted to rainfall rates by applying a Z-R relationship in polar coordinates. The polar grid is then averaged to a rectangular grid (Krajewski and Smith 2002). The default Z-R relationship is empirically derived from both convective and stratiform events is given as:

$$Z=300\ R^{1.4} \tag{1}$$

where Z is the reflectivity in dBz and R is the rain rate in mm h^{-1} (Hunter 1996; Fulton et al. 1998).

Droplet size distribution fluctuates so rapidly that it is nearly impossible to have a single Z-R relation for any length of time for a radar's entire range. The coefficients of the Z-R relationship change according to droplet size, types of precipitation, the mixing of precipitation types, and geographic location (National Oceanic and Atmospheric Administration 2005).

Z-R relationships assume that liquid drops are small compared to the radar wavelength. However, hail and bright band contamination can prove troublesome with this assumption (Hunter 1996). An improper Z-R relationship, miscalibrated radar, overshooting of cloud systems, and evaporation of raindrops beneath a cloud can all cause radar to incorrectly estimate rainfall amounts (Krajewski and Smith 2002).

3.1.4 Meteorological Data

In order to understand the local and regional atmospheric phenomenon influencing weather over Atlanta on high and low aerosol days, meteorological data were needed. Thermodynamic Skew-T Log-P diagrams were obtained from the Plymouth State Weather Center website for the KFFC site (http://vortex.plymouth.edu/). Daily weather maps prepared by the National Centers for Environmental Prediction (NCEP) and Hydrometeorological Prediction Center (HPC) were also obtained (http://www.hpc.ncep.noaa.gov/). These maps consisted of surface and 500 hPa maps at 1100Z of each day, precipitation maps showing the area that had precipitation during the 24 hours ending at 1100 UTC, and daily maximum and minimum temperatures for the given day. Surface wind speeds and directions were obtained from NCDC for the Hartsfield-Jackson International Airport in Atlanta. Wind roses were created for each day of the week and for high and low aerosol days to observe any changes in prevailing wind directions or speeds.

3.2 Methodology

3.2.1 Air Mass Type

Only "synoptically benign" days were considered to limit precipitation mechanisms to convective development. In other words, in order to observe an atmosphere that is predominately influenced by the urban environment, an analysis of days in the data set only reflecting an MT air mass was used. Sheridan (2007) stated that counting both MT and MT+ as MT is appropriate. For purposes of this study, the MT and MT+ air mass types from the SSC were both used to indicate the presence of a warm and humid air mass and the combination of the two will be referred to as MT hereafter.

The use of only one air mass type will allow for a control for days with a similar synoptic setting.   The MT air mass was used because atmospheric instability and convective activity are most common with this type of air mass and the atmospheric is synoptically benign, without the presence of other forms of synoptic forcing (i.e., mid-latitude cyclone, frontal lifting). The SSC indicates that for 1945-2006 the MT air mass resides over Atlanta more often than any other air mass type for each summer month (June-August) (Sheridan 2007). The frequency of days each air mass was present in Atlanta for the POR and for each individual day of the week were also found.

3.2.2 Aerosol

Daily average PM 2.5 concentrations in which an MT air mass resided in Atlanta were identified. The PM 2.5 data were then separated and averaged for each individual day of the week for the Doraville, Decatur, and Atlanta EPA stations. McGrew and Monroe (2000) describe a one-way analysis of variance (ANOVA) that tests multiple samples for differences. This was performed on each individual day of the week for each station. The null hypothesis would mean that each day was from the same population and the alternate hypothesis assumed that each day of the week was from separate and distinct populations.

To compare PM 2.5 concentrations on individual days of the week, 21 two-sample t-tests were conducted. These were performed to determine if PM 2.5 concentrations increased or decreased on any specific day of the week. The initial hypothesis assumed that the daily mean concentrations were considered equal to one another for every day of the week. T-statistics and p-values were analyzed at the 95% confidence level.

A box-and-whisker plot was created for each of the three EPA stations. This type of analysis indicates whether a distribution is skewed and if there are potential unusual observations in the data set. Box-and-whisker plots are ideal for comparing distributions because the median, spread, and overall range are immediately apparent. These figures were aggregated by day of the week and indicated PM 2.5 concentration values for each day.

3.2.3 Radar

A shell script was used to obtain the radar data and to extract only DPA files from the Level III radar data on days when a MT air mass was present in Atlanta. The NCDC Java NEXRAD Viewer and Data Exporter (NCDC 2006) was used to convert the Level-III NWS

WSR-88D NEXRAD radar data into ESRI ASCII grid files. All computed ESRI ASCII grid files were imported into ArcMap and converted to a raster format with a North Pole Stereographic projection. These files were then projected onto maps with northern Georgia counties.

An Interactive Data Language (IDL) program was utilized to calculate the average precipitation amount, total amount of precipitation, and the standard deviation from the average precipitation amounts for each grid point in all of the obtained ESRI ASCII grid files. In order to observe if mean precipitation amounts were due to a few, intense rainfall events or from several, weak rainfall events, a frequency count of radar scans with measurable precipitation (> 0.00 mm) was included. In order to observe any spatial pattern in precipitation amounts, the DPA ESRI ASCII grid files were aggregated into days of the week. A Perl program was used to compute average precipitation amounts for each day of the week for each grid point in order to observe any weekly cycle in mean precipitation totals.

Using IDL, a Wilcoxon signed-ranks test was conducted to test each day of the week against one another to see if there was a significant difference in precipitation amounts between any two days of the week. The Wilcoxon signed-ranks test is a nonparametric test used when data are collected at two different time periods (McGrew and Monroe 2000). The null hypothesis assumes that the sample populations have the same mean of distribution. However, the alternative hypothesis is that the mean of distributions differ with statistical significance at the 95% confidence level (Walpole and Myers 1985). The output ESRI ASCII grid file of this statistical test contained p-values for each grid point. A difference between the two days was then created by masking out the insignificant grid points.

3.2.4 Analysis between PM 2.5 Concentrations and Precipitation Amounts

An examination of aerosol concentrations and precipitation amounts within the metro-Atlanta area was conducted. Days were stratified as high aerosol, low aerosol, or neither. A high aerosol day was defined by any day's average PM 2.5 concentration to be equal to or above one-half standard deviation above the mean PM 2.5 concentration of all days with an MT air mass. Conversely, a low aerosol day was identified by days with an average PM 2.5 concentration equal to or less than one-half standard deviation below the mean of all MT days. The choice of using one-half standard deviations was done in order to obtain a sufficiently large sample size for both high and low aerosol days.

Average precipitation amounts and frequency counts were computed and displayed in separate ESRI ASCII grid files for high and low aerosol days. ASCII files were also created for a difference of means and a difference of frequency counts between the high and low aerosol days. A Wilcoxon signed-ranks test was used to observe any significant differences in precipitation amounts between high and low aerosol days.

3.2.5 Synoptic Analysis

Skew-T log-P diagrams were used to understand the convective potential and instability present in the atmosphere on the high and low aerosol days. These diagrams provide surface and upper-air information on temperature, dew point, wind speed and direction, and several calculated severe weather indices. The convective available potential energy (CAPE) and convective inhibition (CIN) indices are useful for understanding the possible initiation of convection. CAPE measures the energy available to an air parcel in a buoyant updraft. CIN measures the strength of a capping inversion which suppresses or delays the development of convection. For high and low aerosol days, the mean and median values for CAPE and CIN were calculated. Analysis of the temperature profiles provided information on the height of the mixing layer for both types of days. This showed the vertical distance from the surface that pollution could be dispersed through.

Daily weather maps prepared by the National Centers for Environmental Prediction (NCEP) and Hydrometeorological Prediction Center (HPC) were obtained for high and low aerosol days. This helped to understand the surface and upper-level features influencing Atlanta. Daily weather maps consist of surface and 500 hPa maps at 1100Z of each day, precipitation maps for 24-hr accumulations ending at 1100Z, and daily maximum and minimum temperatures for the given day.

CHAPTER 4

RESULTS

Air mass type and 2.5 µm particulate matter (PM 2.5) concentrations were analyzed for 2003-04 at Atlanta to ascertain the role of aerosols on precipitation distribution. Air mass type data was obtained from the spatial synoptic classification (SSC) (Sheridan 2007) and were analyzed by finding the frequency of days each air mass resided in Atlanta. PM 2.5 concentrations were obtained for three EPA aerosol monitoring stations, and frequencies and statistical analyses were completed by day of the week for each station, as well as an analysis between the stations. Radar data were obtained for the Peachtree City, GA (KFFC), and six-minute digital precipitation array (DPA) files were analyzed for daily mean precipitation and precipitation frequencies across metropolitan-Atlanta. The following sections examine each data set in detail, with the final section examining the relationship between PM 2.5 concentration and estimated precipitation amounts.

4.1 Analysis of Air Mass Type

Air mass data from the SSC were analyzed for the summer months (June-August) of 2003 and 2004 in Atlanta, GA. The MT air mass resided over the area for 44% the days in the study's POR (Figure 4.1.1a). The MM inhabited the Atlanta area for 38% of the days and the DM air mass for about 11% of the days. These three air mass types accounted for about 93% of the air mass types for the summer months in Atlanta. The dominance of these three air mass types suggested that warm air masses characterize the Atlanta area through the entire summer.

Air mass residence time was broken down by each month of the POR for each air mass type over Atlanta. For the month of June, the MT, MM, and DM air masses accounted for 31.7%, 48.3%, and 13.3% of the residing time over Atlanta, respectively (Figure 4.1.1b). July exhibited a different frequency for each air mass type, where the MT air mass is over Atlanta 46.8% of the month, with DM and MM residing 11.3% and 35.5% of the time, respectively (Figure 4.1.1c). Similar frequencies are found for August, with the MT air mass present 53.2% of the time, DM 8.1%, and MM 30.7% (Figure 4.1.1d). The MT air mass dominated the Atlanta area during the summer months in Atlanta. The significance of this is that the MT air mass typically is present when no other forcing mechanisms are nearby.

4.2 Analysis of PM 2.5 Concentrations

The daily averages of PM 2.5 concentrations were obtained from three metro-Atlanta EPA stations for 2003-04. Only days with an MT air mass type were used. The three stations were located in Decatur, Doraville, and Atlanta, GA (Figure 3.1.1).

A one-way analysis of variance (ANOVA) was conducted at each of the three stations to determine if PM 2.5 concentrations were higher or lower on any particular day of the week. Each sample assumed a null hypothesis that all seven daily averages were equal at the 95% confidence level.

To make day versus day comparisons, a two-sample difference of means t-test was conducted. Two-tailed t-tests were performed because the study made no a priori assumptions

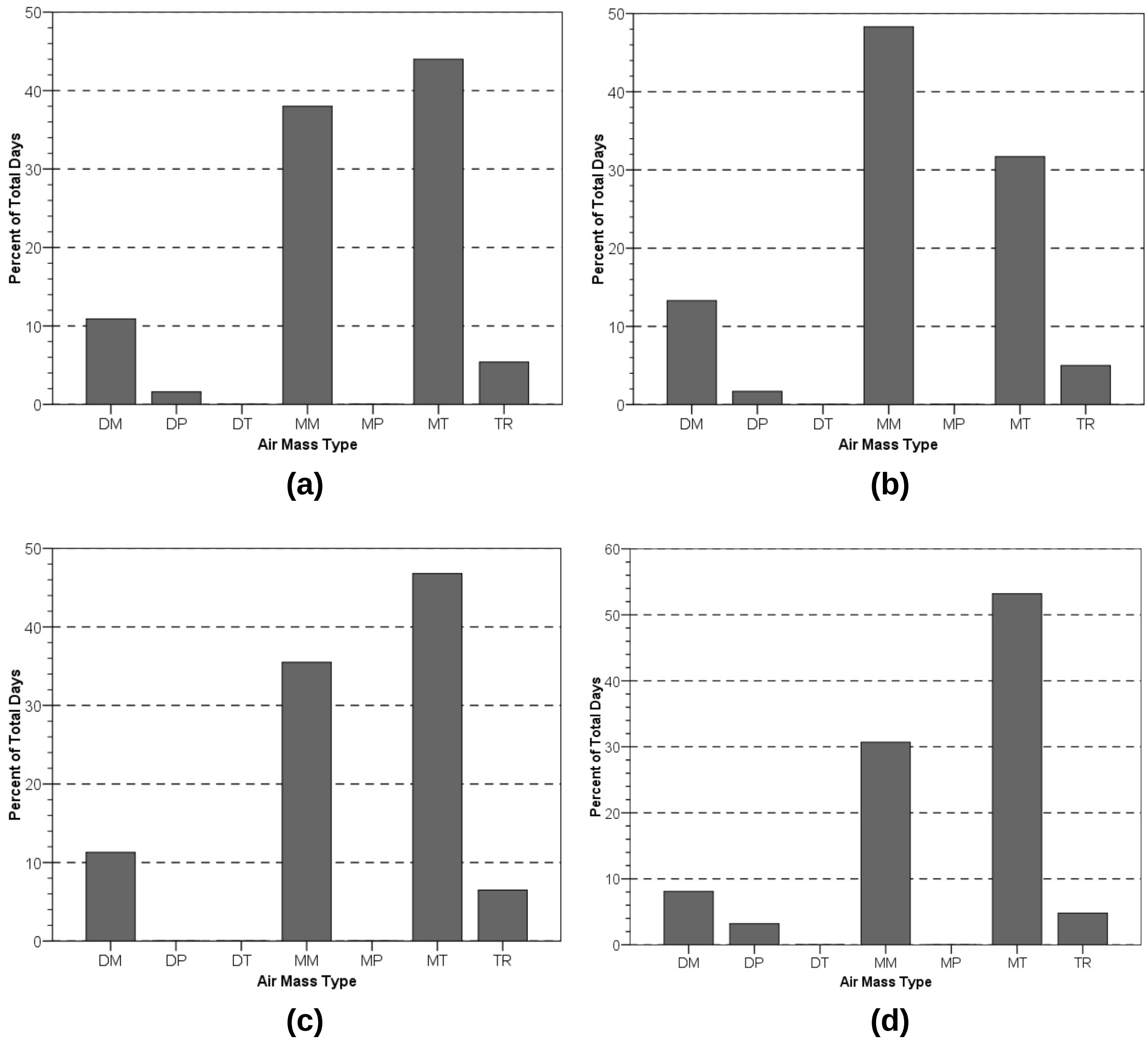


Figure 4.1.1. Percent of days each air mass type during 2003-04 was present in Atlanta for: (a) the period of record, (b) June, (c) July, and (d) August.

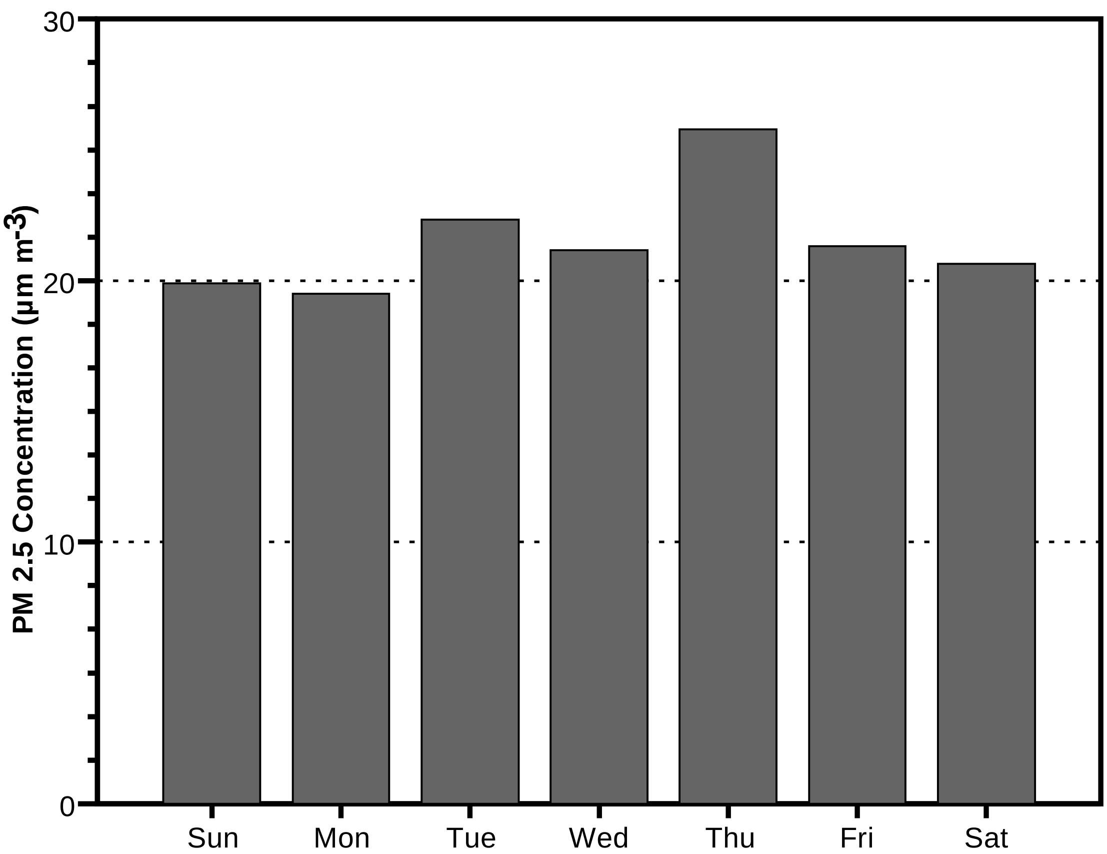


Figure 4.2.1. The daily average PM 2.5 concentrations for the Decatur, GA, station during the summer months of 2003-04.

regarding which days would have larger PM 2.5 concentrations. It was necessary to run 21 separate t-tests for each station to test the null hypothesis of equality for all possible pairs of days.

4.2.1 Decatur station

The Decatur station showed a peak in average PM 2.5 concentrations during Tuesday-Friday with the lowest average concentrations occurring on Saturday-Monday (Figure 4.2.1).

Table 4.2.1. F-statistic, p-value, and critical F values from an ANOVA test on the daily frequencies of PM 2.5 at the Decatur, GA, station.

F-statistic	p-value	Critical F
0.714	0.639	2.240

Table 4.2.2. The t-statistics from two-tailed day vs. day comparisons of PM 2.5 concentrations for the POR at the Decatur, GA, station at the 95% confidence level.

	Sun	Mon	Tue	Wed	Thu	Fri
Mon	0.156					
Tue	-1.193	-1.236				
Wed	-0.352	-0.441	0.547			
Thu	-1.503	-1.540	-0.574	-0.968		
Fri	-0.443	-0.534	0.557	-0.036	0.995	
Sat	-0.277	-0.392	0.845	0.135	1.241	0.193

The highest average concentration of PM 2.5 occurred on Thursday at 25.78 micrograms per cubic meter ($\mu g/m^3$). Monday showed the lowest average concentration at 19.5$\mu g/m^3$.

The results of the one-way ANOVA for each individual day are given in Table 4.2.1. The data at this site yielded a p-value of 0.639 at the 95% confidence level. Because this p-value is greater than 0.05, the days of the week were not significantly different from one another.

The results of the t-test analyses on pairs of days from the daily averaged PM 2.5 concentrations are shown in Table 4.2.2. The comparison of Wednesday with Friday was the only daily comparison to show a significant difference at the 95% confidence level (Table 4.2.3). A t-test was also conducted at the 90% confidence level (not shown), and there was no significance between the 21 comparisons.

Figure 4.2.2 is a box-and-whisker plot of the differences in PM 2.5 concentrations by day of the week for the Decatur station during 2003-04. The box limits are plotted at the lower (25%) and upper (75%) quartiles of the respective PM 2.5 concentrations. The whiskers (vertical

Table 4.2.3. The p-values from two-tailed day vs. day comparisons of PM 2.5 concentrations for the POR at the Decatur, GA, station at the 95% confidence level.

	Sun	Mon	Tue	Wed	Thu	Fri
Mon	0.878					
Tue	0.253	0.237				
Wed	0.731	0.666	0.593			
Thu	0.161	0.148	0.575	0.347		
Fri	0.332	0.599	0.584	0.971	0.334	
Sat	0.785	0.700	0.411	0.895	0.237	0.895

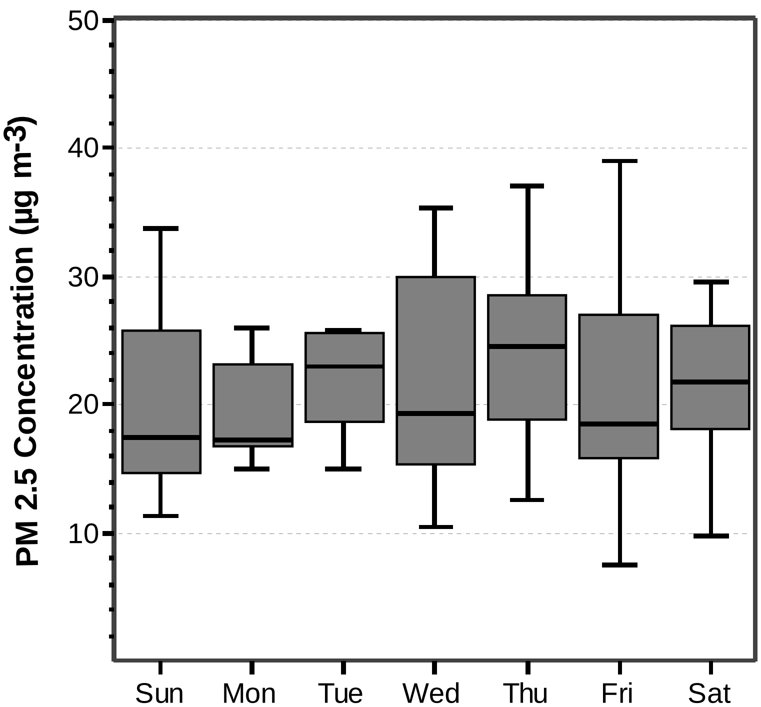


Fig 4.2.2. Box-and-whisker plot of the daily PM 2.5 concentration for the Decatur, GA, station during the summers of 2003-04 with a MT air mass present. The plots represent the interquartile range (shaded), the median (thick line), and outliers (the 10^{th} and 90^{th} percentiles as whiskers). The average PM 2.5 concentration per day is indicated along the y-axis.

lines) extend to the smallest and largest concentration values for each day. Also, the thick lines in the center of the boxes indicate the calculated medians.

This box-and-whisker plot indicates that Thursday is the day that had the highest median concentration followed by Tuesday. The plot also indicated that Wednesday had the most variability in concentration values, illustrated by the whiskers and larger interquartile range compared to the rest of the week. Monday appeared to have the lowest median value. Figure 4.2.2 does not appear to show a weekly cycle in PM 2.5 concentrations at this station.

4.2.2 Doraville station

The Doraville station showed a mid-week peak (Tuesday-Thursday) in mean PM 2.5 concentrations (Figure 4.2.3). Thursday had the highest average concentration with 25.11 $\mu g/m^3$ compared to the lowest average on Sunday at 18.76 $\mu g/m^3$.

The ANOVA test showed a p-value of about 0.59 at the 95% confidence level (Table 4.2.4). Each day of the week was not significantly different from one another because the calculated p-value was greater than 0.05. The t-test analyses on pairs of days from the daily averaged PM 2.5 concentrations are shown in Table 4.2.5. None of the 21 comparisons were found to be significant at the 95% (Table 4.2.6) or 90% (not shown) confidence levels.

A box-and-whisker plot is shown in Figure 4.2.4 for the Doraville station. PM 2.5 concentrations are shown by day of the week for 2003-04. When observing the median values (the thick lines), Thursday had the highest concentration, followed by Tuesday and Friday. Wednesday had the largest range of and highest measured concentration values yet had the second lowest median concentration value. This indicated that the mean value calculated for

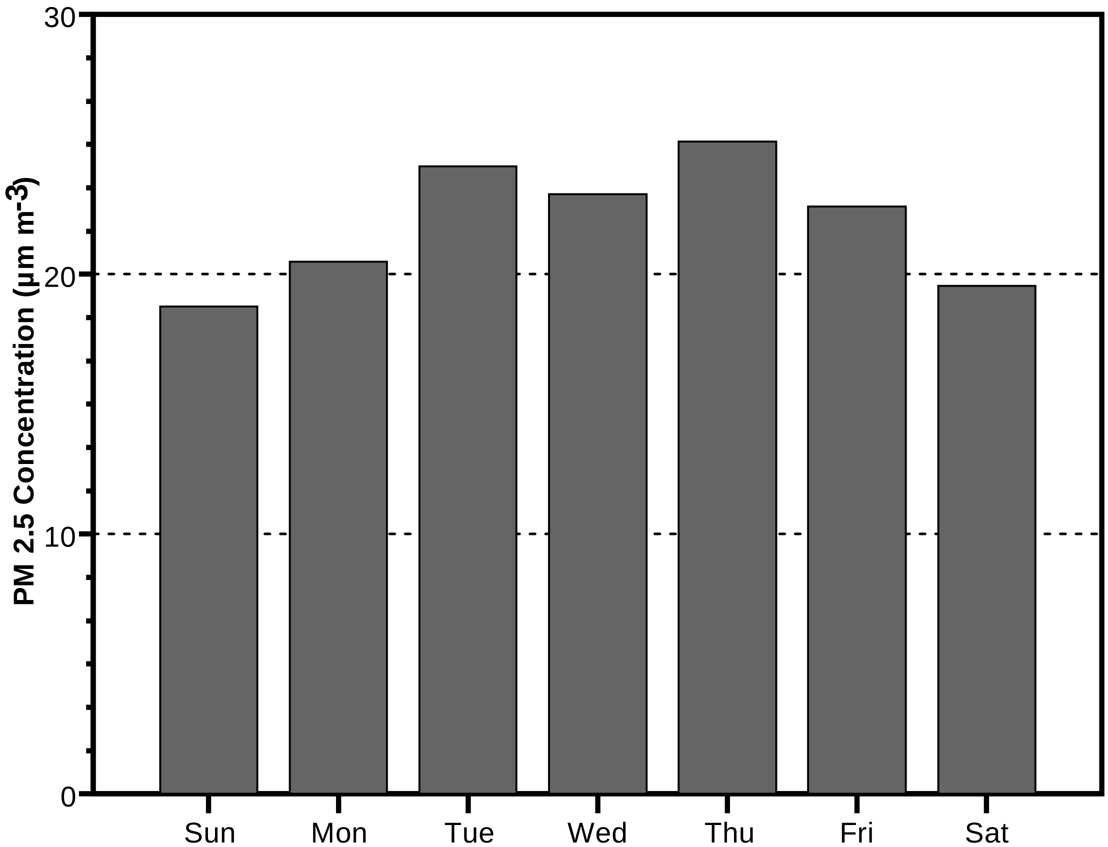


Figure 4.2.3. Same as Figure 4.2.1 except for the Doraville, GA, station.

Table 4.2.4. Same as Table 4.2.1 except for the Doraville, GA, station.

F-statistic	p-value	Critical F
0.778	0.599	2.227

Table 4.2.5. Same as Table 4.2.2 except for the Doraville, GA, station.

	Sun	Mon	Tue	Wed	Thu	Fri
Mon	-0.657					
Tue	-1.236	-0.833				
Wed	-0.940	-0.560	0.187			
Thu	-1.592	-1.145	-0.177	-0.367		
Fri	-1.161	-0.628	0.321	0.094	0.555	
Sat	-0.302	0.341	1.040	0.758	1.371	0.900

Table 4.2.6. Same as Table 4.2.3 except for the Doraville, GA, station.

	Sun	Mon	Tue	Wed	Thu	Fri
Mon	0.517					
Tue	0.245	0.425				
Wed	0.368	0.587	0.855			
Thu	0.132	0.269	0.862	0.718		
Fri	0.261	0.538	0.753	0.926	0.585	
Sat	0.766	0.737	0.323	0.465	0.191	0.381

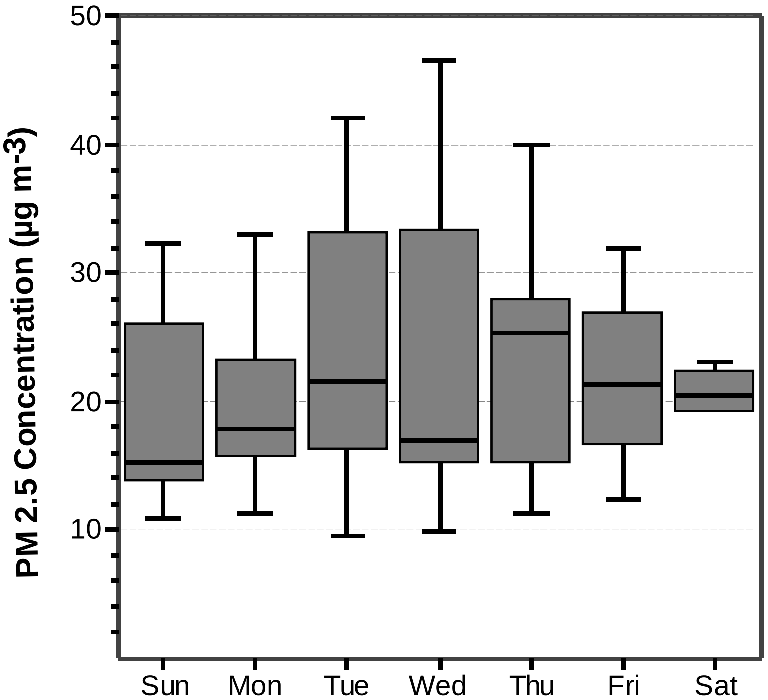


Fig 4.2.4. Same as Figure 4.2.2 except for the Doraville, GA, station.

Wednesday, which was shown to be the third largest when compared to every other day of the week (Figure 4.2.4), was right skewed. This skewness is shown in Figure 4.2.3 by observing the fairly high concentration value for the outlier at the 90% quartile (the upper whisker). The Doraville station would appear to have a weekly cycle of pollution amounts that peaks during the weekdays, had it not been for Wednesday's low median concentration value.

4.2.3 Atlanta Station

The Atlanta station displayed results similar to the other two stations. There was a mid-week peak in PM 2.5 concentrations (Figure 4.2.5). The mean concentration for Tuesday was 26.97 $\mu g/m^3$, Wednesday was 24.55 $\mu g/m^3$, and Thursday was 24.71 $\mu g/m^3$. Sunday displayed the lowest average concentration at 20.54 $\mu g/m^3$.

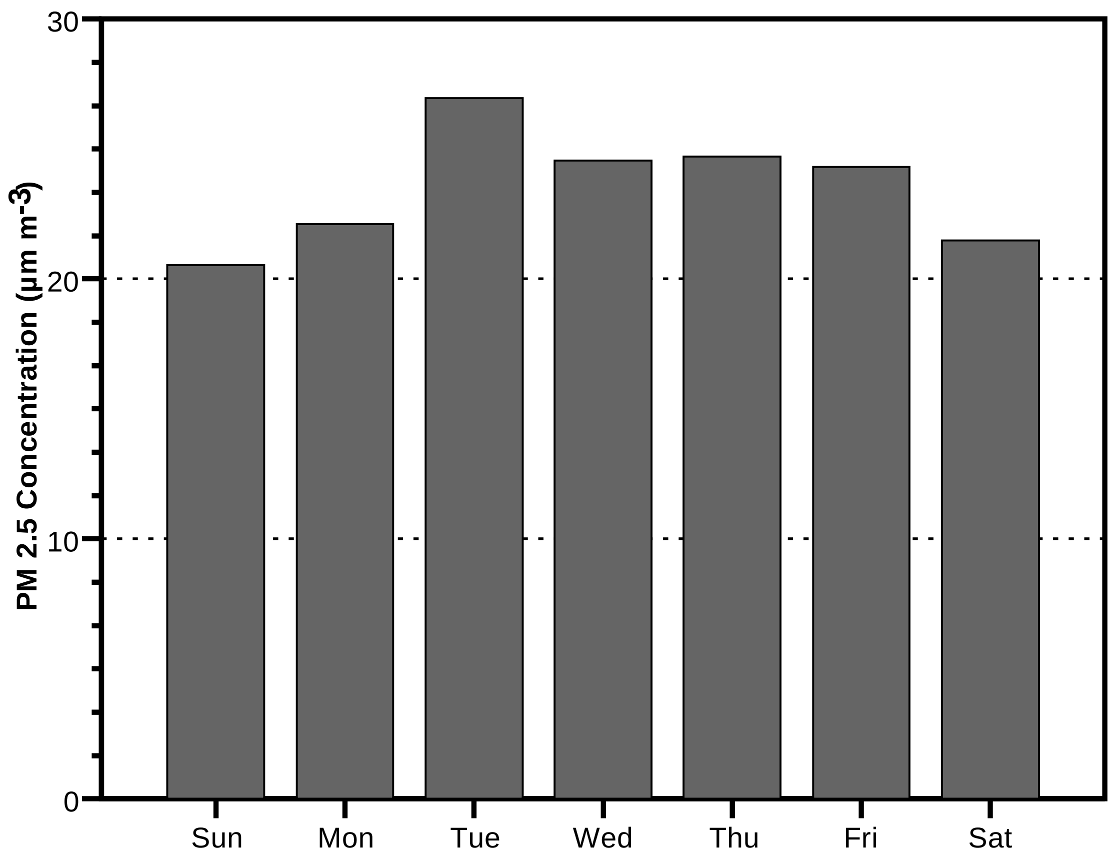


Figure 4.2.5. Same as Figure 4.2.1 except for the Atlanta, GA, station.

Table 4.2.7. Same as Table 4.2.1 except for the Atlanta, GA, station.

F-statistic	p-value	Critical F
0.659	0.683	2.235

Table 4.2.8. Same as Table 4.2.2 except for the Atlanta, GA, station.

	Sun	Mon	Tue	Wed	Thu	Fri
Mon	-0.587					
Tue	-1.645	-1.130				
Wed	-0.963	-0.510	0.516			
Thu	-1.068	-0.574	0.505	-0.030		
Fri	-0.973	-0.484	0.586	0.048	0.081	
Sat	-0.425	0.254	1.407	0.731	0.819	0.723

The one-way ANOVA test for this station is displayed in Table 4.2.7. An F-statistic of 0.659 was found with a p-value of 0.683 at the 95% confidence level. This suggests that each aily average PM 2.5 concentration was not statistically different from each other.

The results of the t-test analyses on pairs of days from the daily averaged PM 2.5 concentrations for the Atlanta station are shown in Table 4.2.8. Similar to the Decatur station, the p-value calculated for the Wednesday with Friday comparison was the only daily comparison to show a significant difference at the 95% confidence level (Table 4.2.9). A t-test was also conducted at the 90% confidence level (not shown), and there was no significance between the 21 comparisons.

Figure 4.2.6 shows the box-and-whisker plot for PM 2.5 concentrations at the Atlanta station by day of the week. Tuesday and Thursday had the highest median (solid line) concentrations. One interesting finding was that Wednesday had the second lowest median concentration value even though it had one of the higher mean concentration values. Sunday was shown to have the smallest median values in PM 2.5 concentrations. This pattern matches

Table 4.2.9. Same as Table 4.2.3 except for the Atlanta, GA, station.

	Sun	Mon	Tue	Wed	Thu	Fri
Mon	0.565					
Tue	0.128	0.278				
Wed	0.355	0.618	0.612			
Thu	0.304	0.573	0.620	0.976		
Fri	0.351	0.635	0.566	0.963	0.936	
Sat	0.676	0.803	0.187	0.479	0.427	0.479

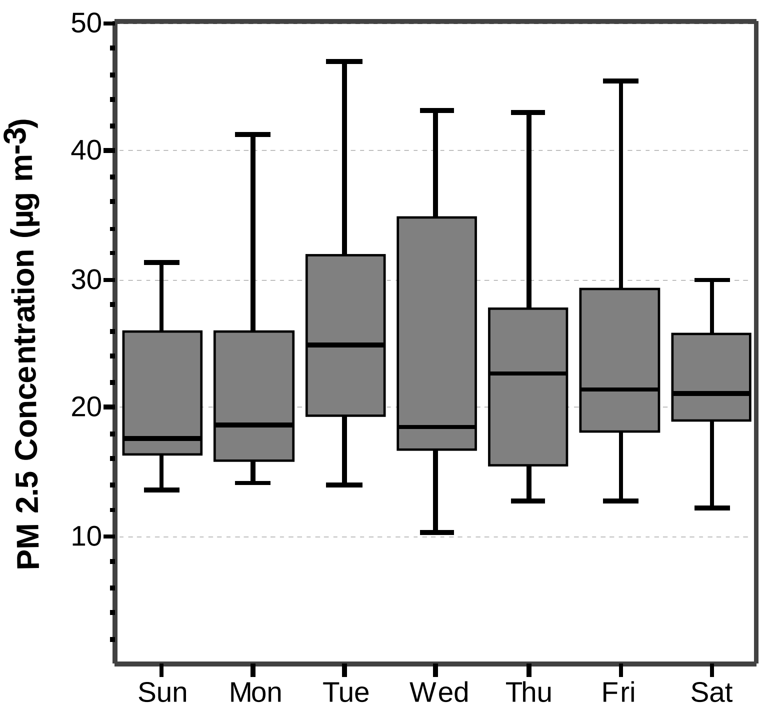


Fig 4.2.6. Same as Figure 4.2.2 except for the Atlanta, GA, station.

closely with what was found at the Doraville station in that there appears to be a weekly cycle in concentration values, but Wednesday's median value discredits this suggestion.

4.2.4 Metro-Atlanta PM 2.5 Station Analysis

A two-sample t-test was conducted among the pairs of PM 2.5 recording stations in the metro-Atlanta area at the 95% confidence level. The null hypothesis assumed that each station is from the same population, while the alternative hypothesis assumed that each station's concentration values were from separate and distinct populations. When observing PM 2.5 concentration values for the summer months (June-August) of 2003-04, the comparison of the Doraville and Decatur stations produced a p-value of 0.788. The same test was conducted for the Decatur and Atlanta (p-value: 0.136) and Doraville and Atlanta (p-value: 0.239) stations. Because each p-value was calculated to be above 0.05, the null hypothesis of equality can be accepted. Thus the three stations were not statistically different from one another.

Another t-test was calculated for the days when Atlanta experienced a MT air mass during the summer months of 2003-04. A comparison between the Doraville and Decatur stations resulted in a p-value of 0.888. The comparisons of Doraville with Atlanta and Decatur with Atlanta resulted in p-values of 0.260 and 0.188, respectively. These results indicate that there is no statistically significant difference between the three stations when an MT air mass is present in Atlanta. The results of the t-tests indicated that the three EPA stations can be expected to show similar PM 2.5 concentrations for the metro-Atlanta area for any summer day with any given air mass present, or specifically, when a MT air mass is present.

4.3 Analysis of Precipitation

NEXRAD WSR-88D radar data were utilized from the Peachtree City, GA, radar (KFFC) to obtain precipitation estimates for the metro-Atlanta area. Radar data were analyzed for the summer months (June-August) of 2003-04. Maps were created for each individual day of the week using mean precipitation values for each grid cell. Days determined to be low or high aerosol days were analyzed in greater detail.

4.3.1 Daily Average Precipitation Amounts Analysis

Maps were created for the summers of 2003-04 when an MT air mass was present in Atlanta (Figure 4.3.1). Figure 4.3.1a displays average precipitation amounts throughout north Georgia. The highest averages appear from the northwest corner of the metro-Atlanta area to the eastern edge. Of this particular area, the counties of northern Bartow, northern Paulding, Walton, northern Newton, and northern Rockdale had the largest mean values. The number of six-minute radar scans when any precipitation was estimated to have fallen is shown in Figure 4.3.1b and showed the highest number of radar scans with a rainfall accumulation located across Paulding and Cobb counties, as well as, parts of northern Fulton and DeKalb counties. The evidence suggests that those areas with the highest occurrence of precipitation led to the highest precipitation amounts within the urban area. A similar pattern is born out in the total amount of precipitation over this time period (Figure 4.3.1c) and the standard deviations (Figure 4.3.1d). The highest total rainfall amounts and standard deviations from the mean occurred in the same locations as the highest means and count values.

When comparing all the images in Figure 4.3.1, the most southern counties of the metro

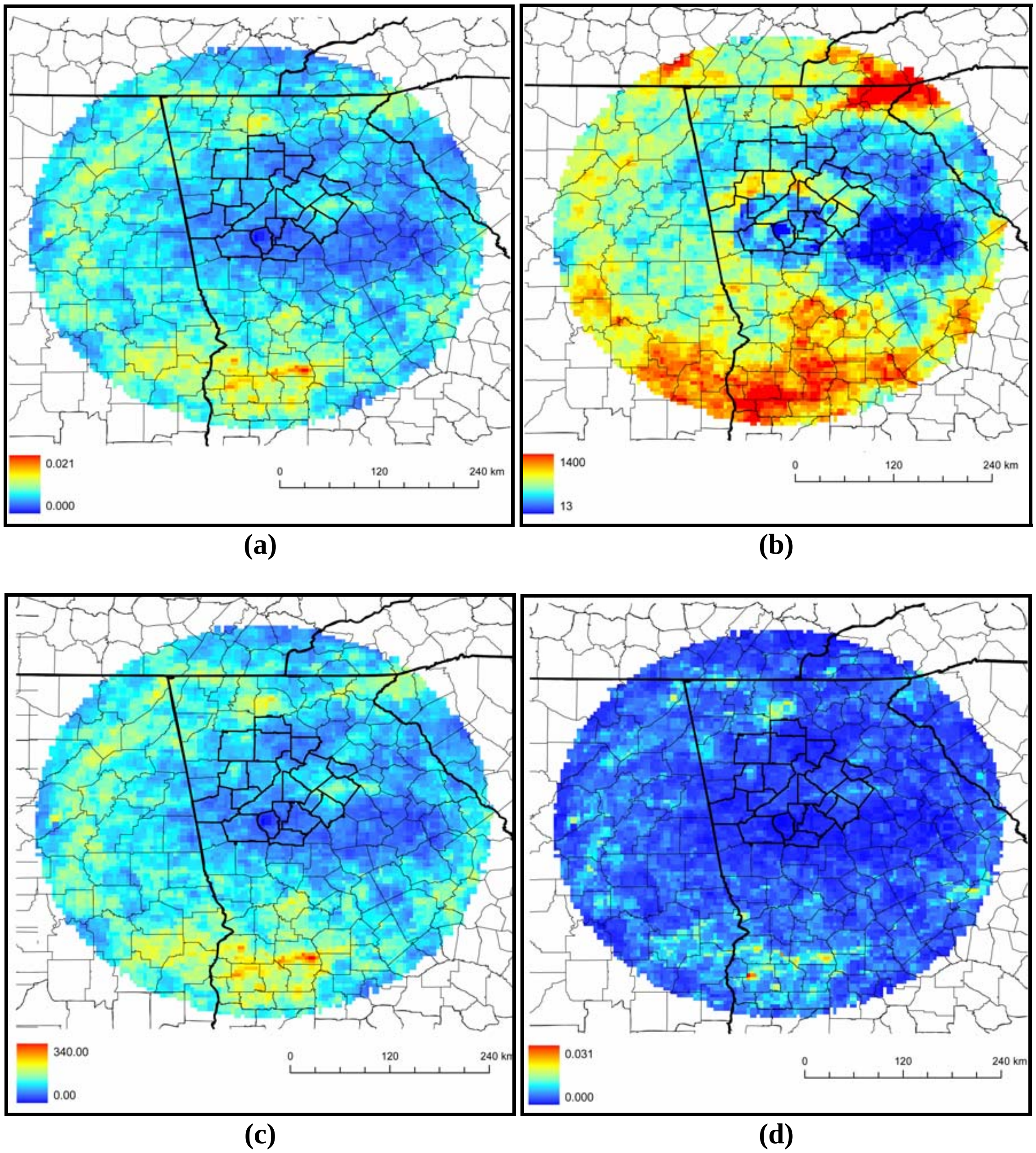


Figure 4.3.1. The summer months (June-August) for 2003-04 are analyzed on days when a MT air mass was present in Atlanta and the following are shown for each grid point: (a) mean precipitation amount (mm/radar scan), (b) frequency count of radar scans with precipitation accumulation, (c) total precipitation amount (mm/radar scan), and (d) standard deviation from the mean (mm/radar scan).

area had the lowest mean values, frequency counts, total amounts, and standard deviation values when compared to the rest of Atlanta's urban region. One interesting finding in some of the images was a ring around the KFFC radar site. This ring possibly resulted from various radar scans overlapping at the melting level aloft which can lead to underestimates of precipitation (Brandes et al. 1999; Westrick et al. 1999). For the purpose of this analysis, this area will not be considered further.

Daily maps were created for the summers of 2003-04 when a MT air mass was present in Atlanta. Appendix A shows the frequency count of radar scans and percent of total radar scans by hour for each day of the week. This information was looked at because of the concern there was a bias of what time of day the majority of the DPA scans occurred. However, no observed bias was found that would greatly affect the results. Figures 4.3.2 through 4.3.8 show the average precipitation amounts by day of the week. On Sundays, the highest average rainfall amounts in the Atlanta metro-area occurred in Bartow and Paulding Counties (in the west) and Newton and eastern Walton Counties (in the east) (Figure 4.3.2). When observing Monday average precipitation amounts, the eastern half of the metro area, as well as farther east of the city, had higher average amounts of precipitation (Figure 4.3.3). Tuesdays had smaller average precipitation amounts over the entire Atlanta region, as well as across much of Northern Georgia (Figure 4.3.4). This is in stark contrast to Monday (Figure 4.3.3), where there were higher average rainfall amounts found throughout the entire North Georgia area as compared to Tuesday. Figure 4.3.5 shows that Wednesday's average precipitation amounts most closely resembled Sunday's average totals (Figure 4.3.2); the highest average rainfall amounts occurred in Northern Bartow County and the far eastern portions of metro-Atlanta.

Thursday (Figure 4.3.6) had a pattern of higher average precipitation amounts from Paulding and Bartow Counties in the west to Barrow and Walton Counties in the east. Similar rainfall amounts do not extend too far east of Atlanta. On average, the metro area received smaller amounts of precipitation on Fridays (Figure 4.3.7) compared to the rest of North Georgia. On Saturdays (Figure 4.3.8), the largest average amounts occurred sporadically throughout the eastern portion of the metro region. This finding was similar to most of North Georgia in which no geographic pattern was evident, except for possible orographic effects in the northern most areas of Georgia.

When viewing the mean average rainfall amounts for the entire week, the eastern counties of Walton, northern Newton, and northern Rockdale counties and the western counties of Bartow and Paulding counties had the highest precipitation amounts over the course of the entire week when compared to other parts of the region (Figure 4.3.1a). Overall, Monday and Thursday appeared to have the highest average precipitation amounts on days when a MT air mass is present over Atlanta. The main difference between the two days is the spatial pattern in average quantities, when Monday experienced the highest amounts in the eastern half of the metro area and Thursday showed the largest sums distributed over the interior metro area.

Figure 4.1.1 showed the southern most counties in the metropolitan area to have the smallest average precipitation amounts and this was also found when average amounts were observed for every individual day of the week. Fridays and Saturdays contributed the highest amounts of rainfall for this area, yet these days showed amounts to still be smaller when compared to the rest of the metro area.

Wind roses were created from the Hartsfield-Jackson International Airport in Atlanta for each day of the week (Figure 4.3.9). The weakest average wind speeds occurred from the

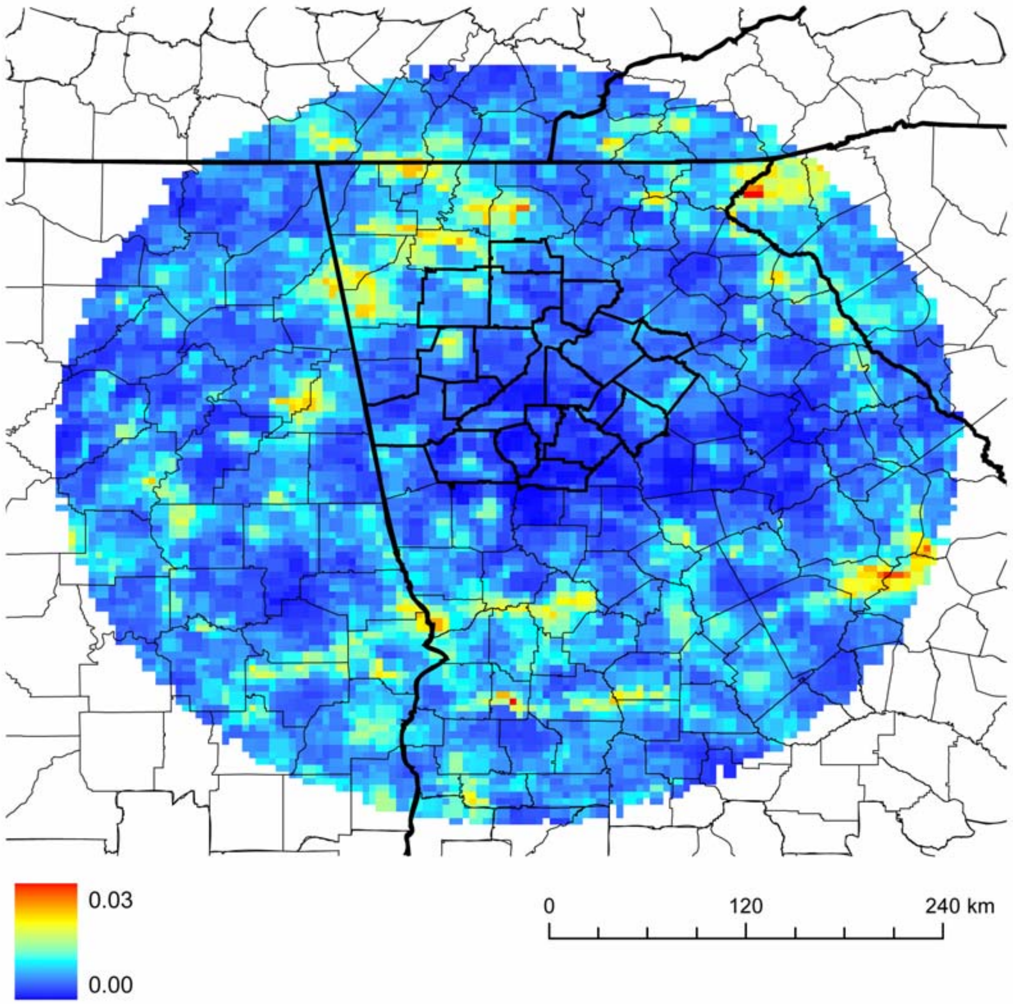


Figure 4.3.2. Average radar estimated precipitation amounts (mm/radar scan) for the summer months (June-August) of 2003-04 on days when a MT air resided in Atlanta, GA, on Sunday.

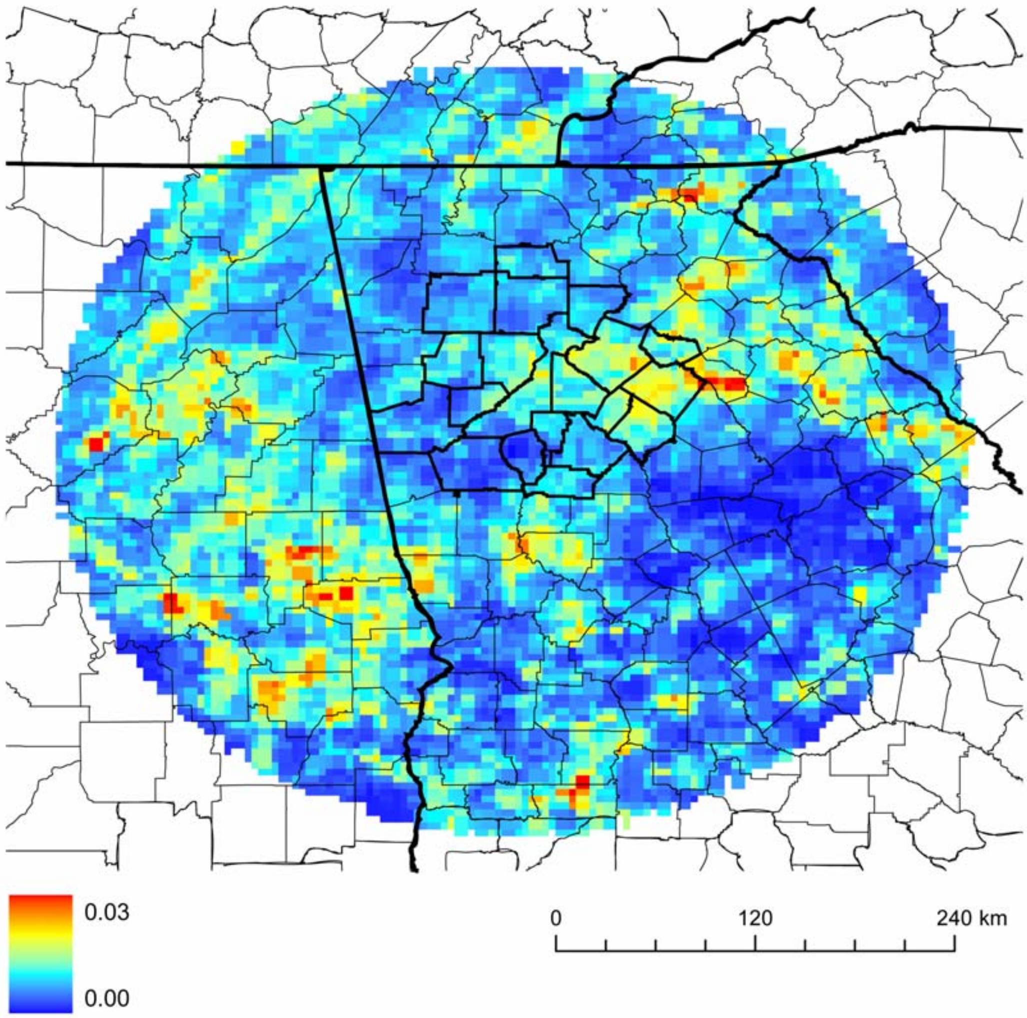


Figure 4.3.3. Same as Figure 4.3.2, except for Monday.

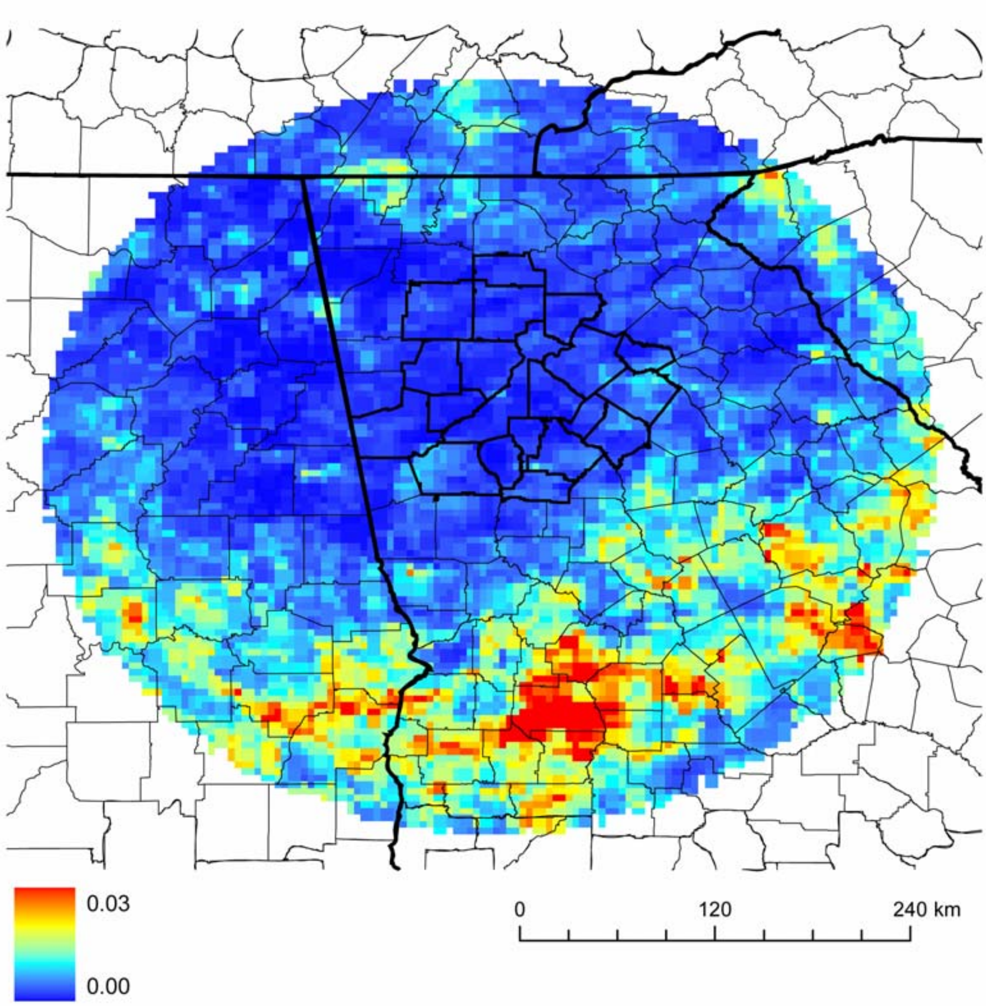


Figure 4.3.4. Same as Figure 4.3.2, except for Tuesday.

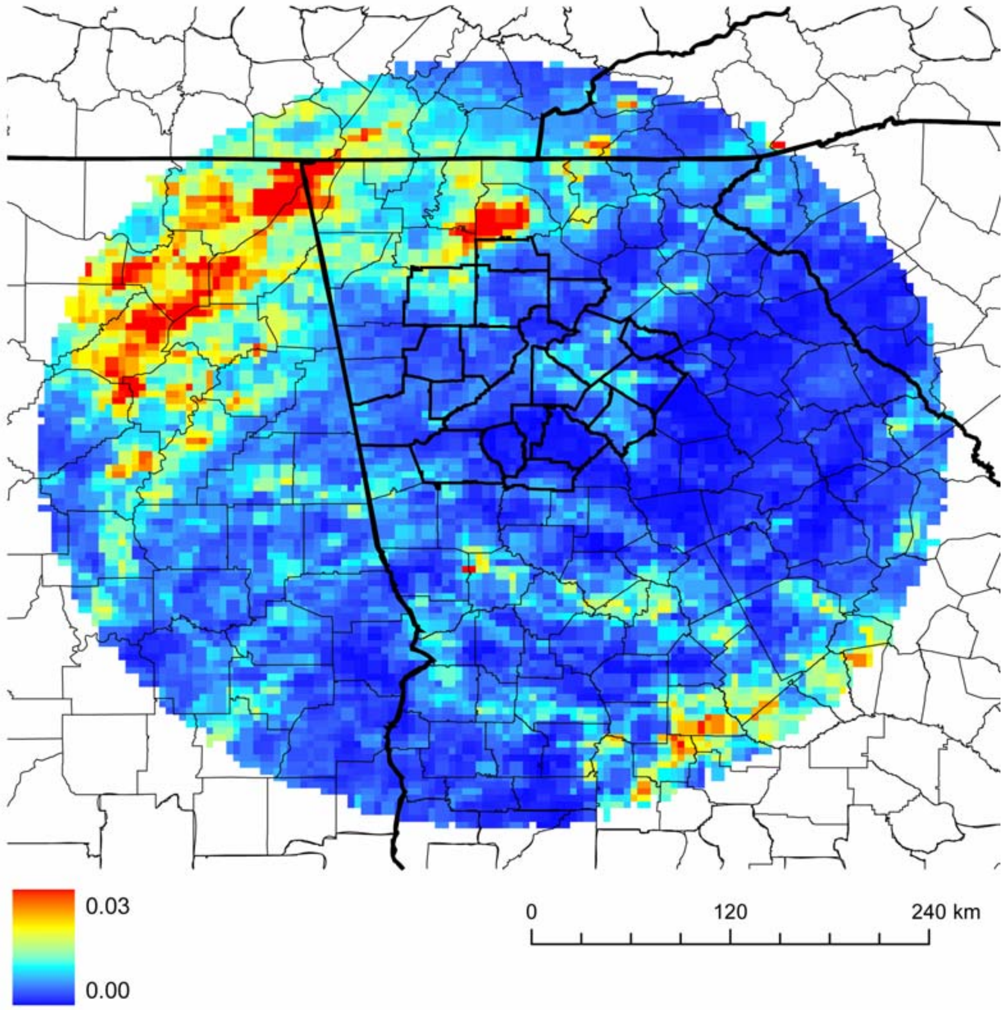


Figure 4.3.5. Same as Figure 4.3.2, except for Wednesday.

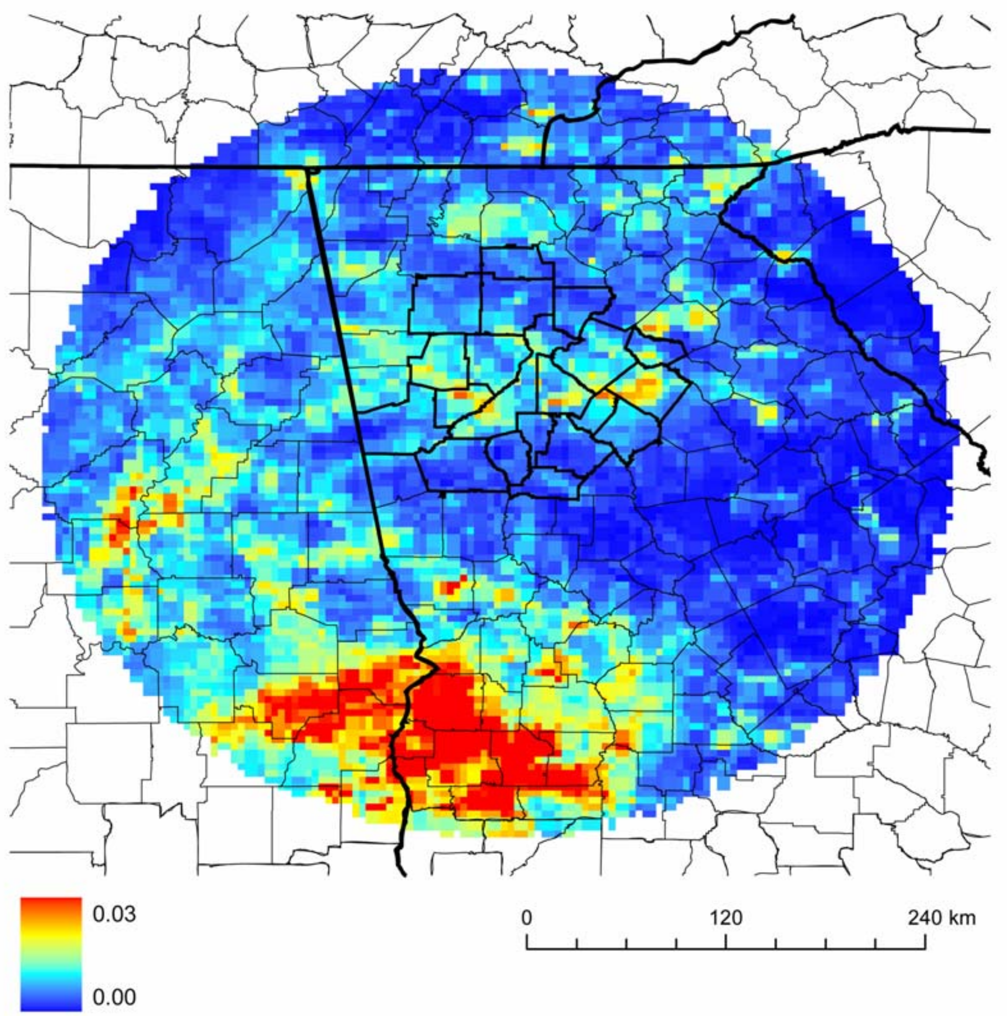


Figure 4.3.6. Same as Figure 4.3.2, except for Thursday.

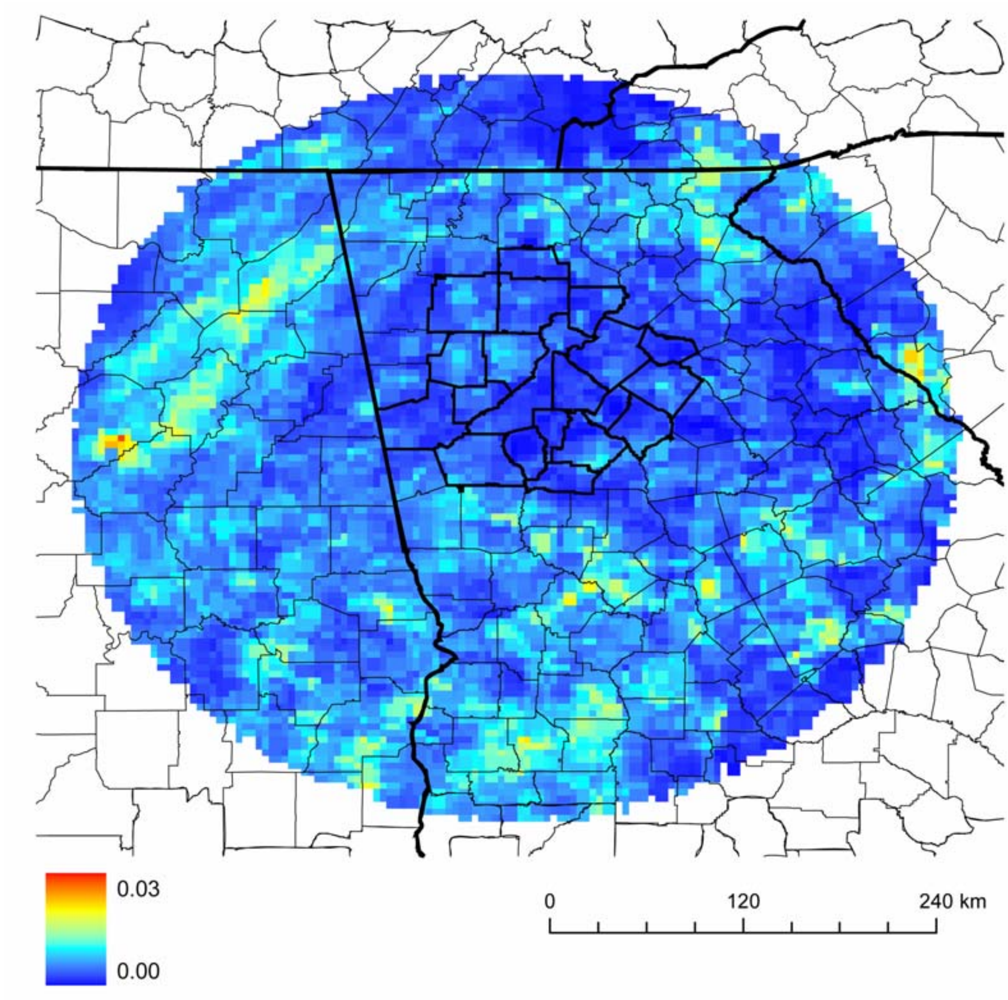


Figure 4.3.7. Same as Figure 4.3.2, except for Friday.

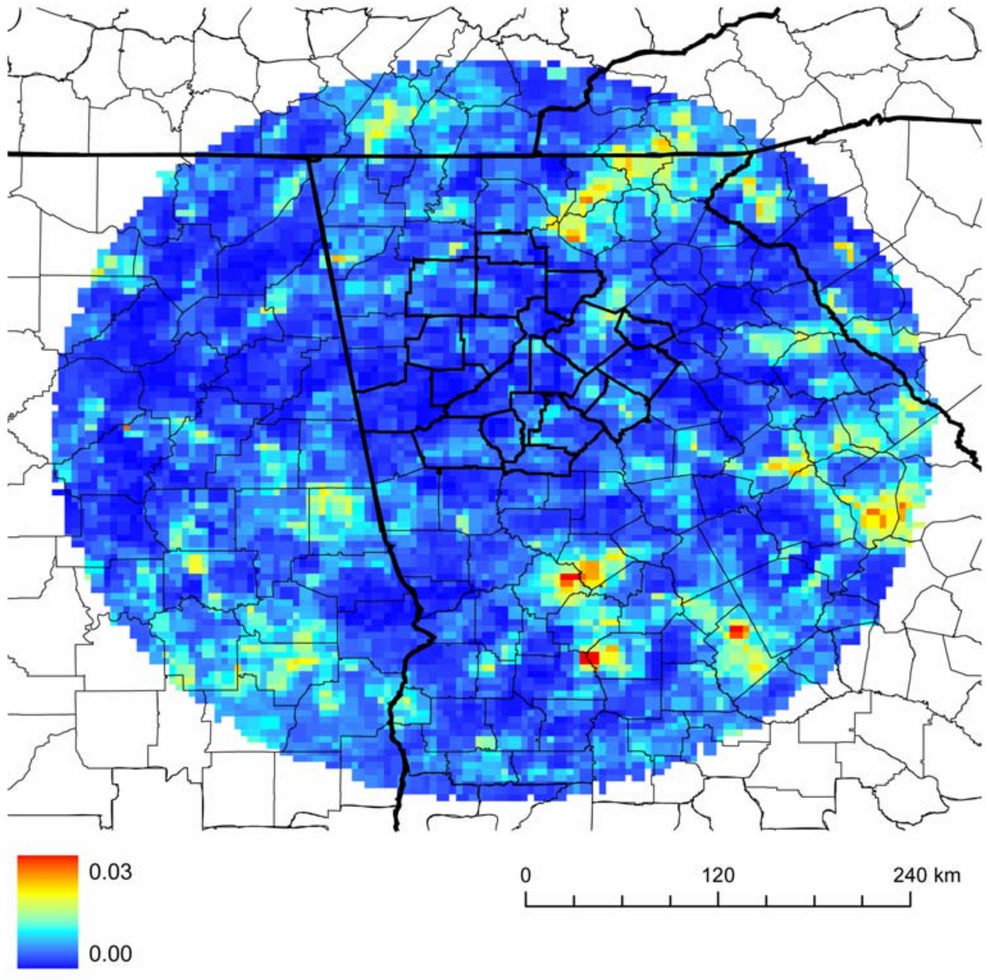


Figure 4.3.8. Same as Figure 4.3.2, except for Saturday.

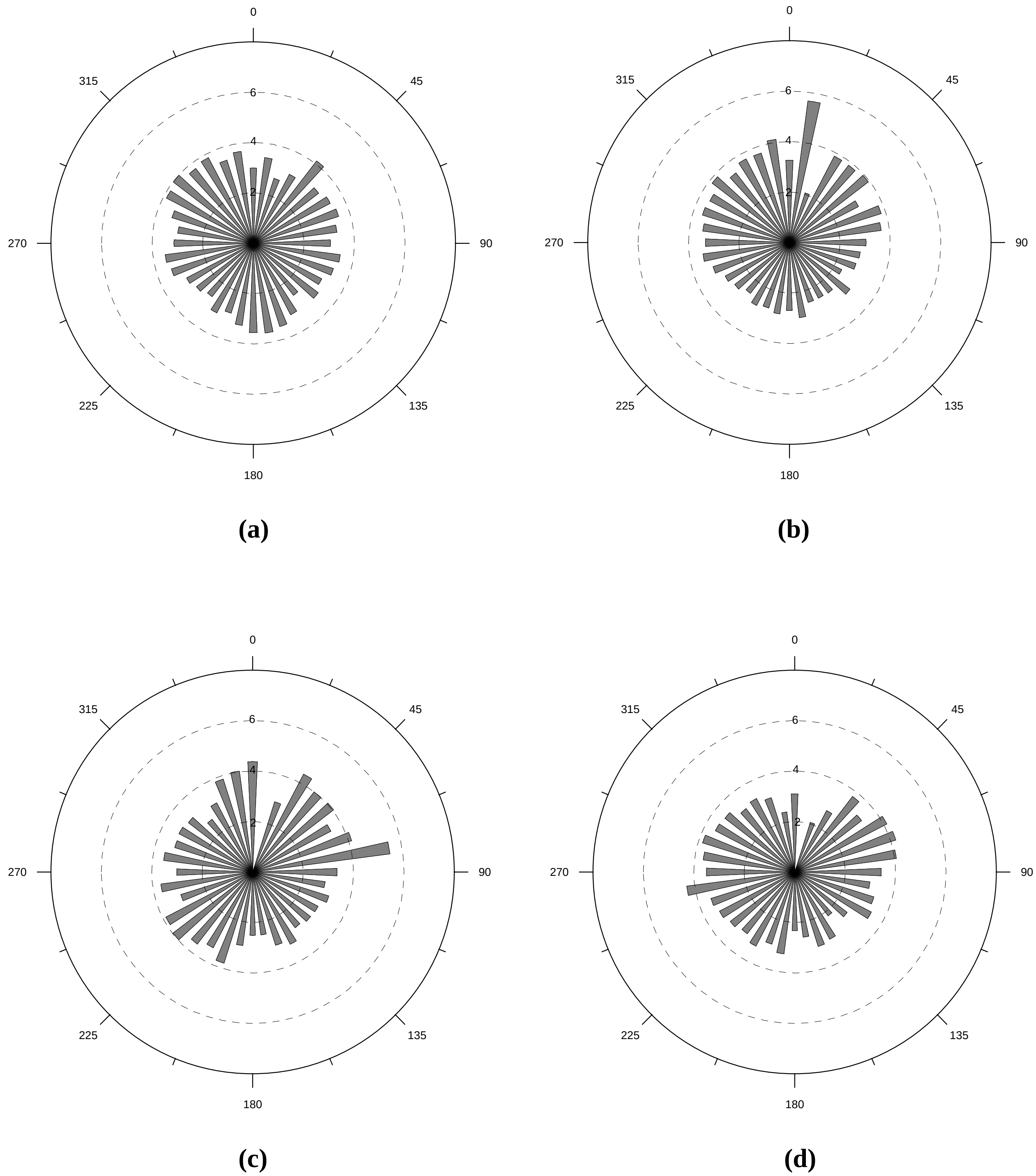
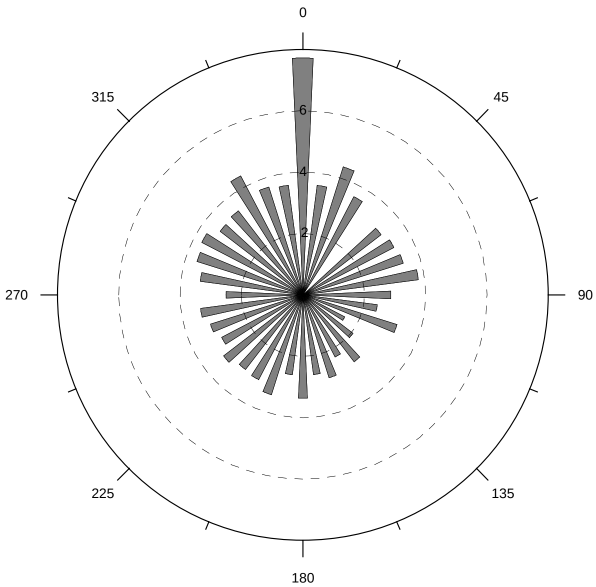
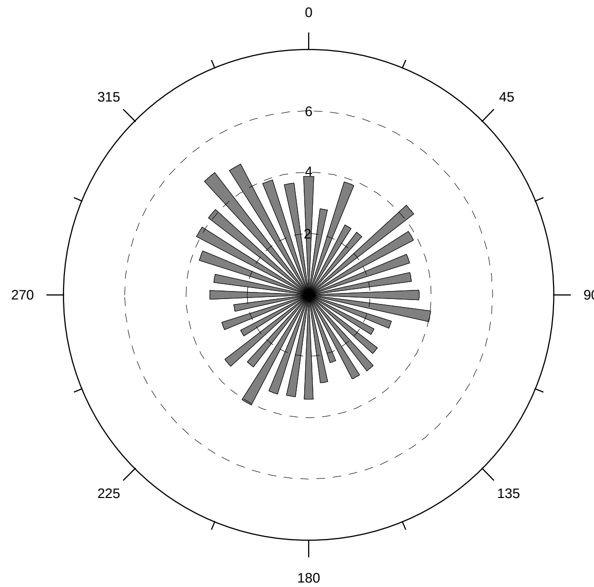


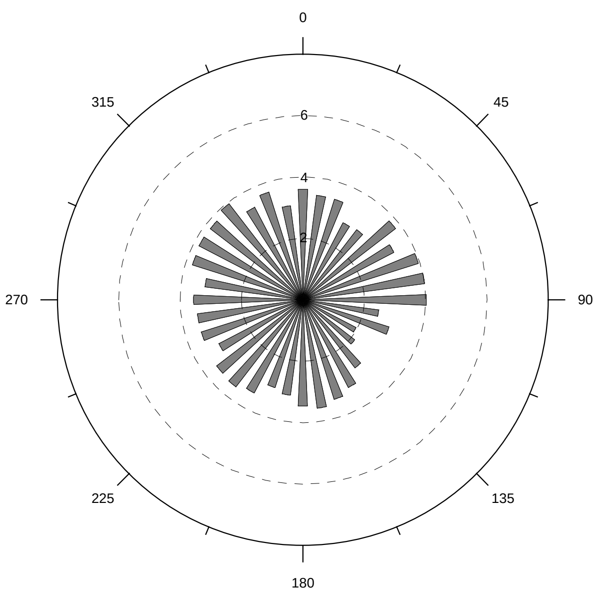
Figure 4.3.9. Wind roses for Atlanta, GA, at the Hartsfield-Jackson International Airport that indicate the average wind speed along the radial axis and the wind direction in degrees is on the angular axis for a) Sunday, b) Monday, c) Tuesday, d) Wednesday, e) Thursday, f) Friday, and g) Saturday.



(e)



(f)



(g)

Figure 4.3.9. continued

southeast quadrant for each day of the week. A strong preference for any generally dominant wind flow was not found for any day of the week.

4.3.2 Analysis of Daily Average Precipitation Amounts

In order to see if there was a statistically significant difference in precipitation amounts on any one day of the week, a Wilcoxon signed-ranks test was performed on each of the 17,161 grid cells. This test was conducted 21 times at the 95% confidence level. The null hypothesis assumed that there was no difference in estimated precipitation amounts between each grid cell for each dual comparison of days. The alternate hypothesis assumed the precipitation amounts for each pair of days were significantly different from each other.

The following tests showed there to be no difference (p-value > 0.05) throughout nearly the entire metro-Atlanta region (not shown): Sunday and Wednesday, Sunday and Friday, Sunday and Saturday, Tuesday and Friday, Tuesday and Saturday, Wednesday and Friday, Wednesday and Saturday, and Friday and Saturday. The other 13 tests showed at least some large part of the metro area had significant differences in daily precipitation amounts.

Figures 4.3.10 and 4.3.11 are difference maps between Sunday with Monday and Monday with Wednesday precipitation means, respectively. Only grid points found to have a significant difference (p-value ≤ 0.05) between the two days are shown. The analysis of Sunday with Monday showed most of the eastern half of the metro area had significantly higher precipitation amounts on Monday and on Sunday in parts of Cherokee, Bartow, and Paulding counties. When Monday was compared with Wednesday, areas that had significantly higher precipitation mounts on Wednesday were located in the eastern half of the metro area and on Monday mostly in Carroll and northern Bartow counties.

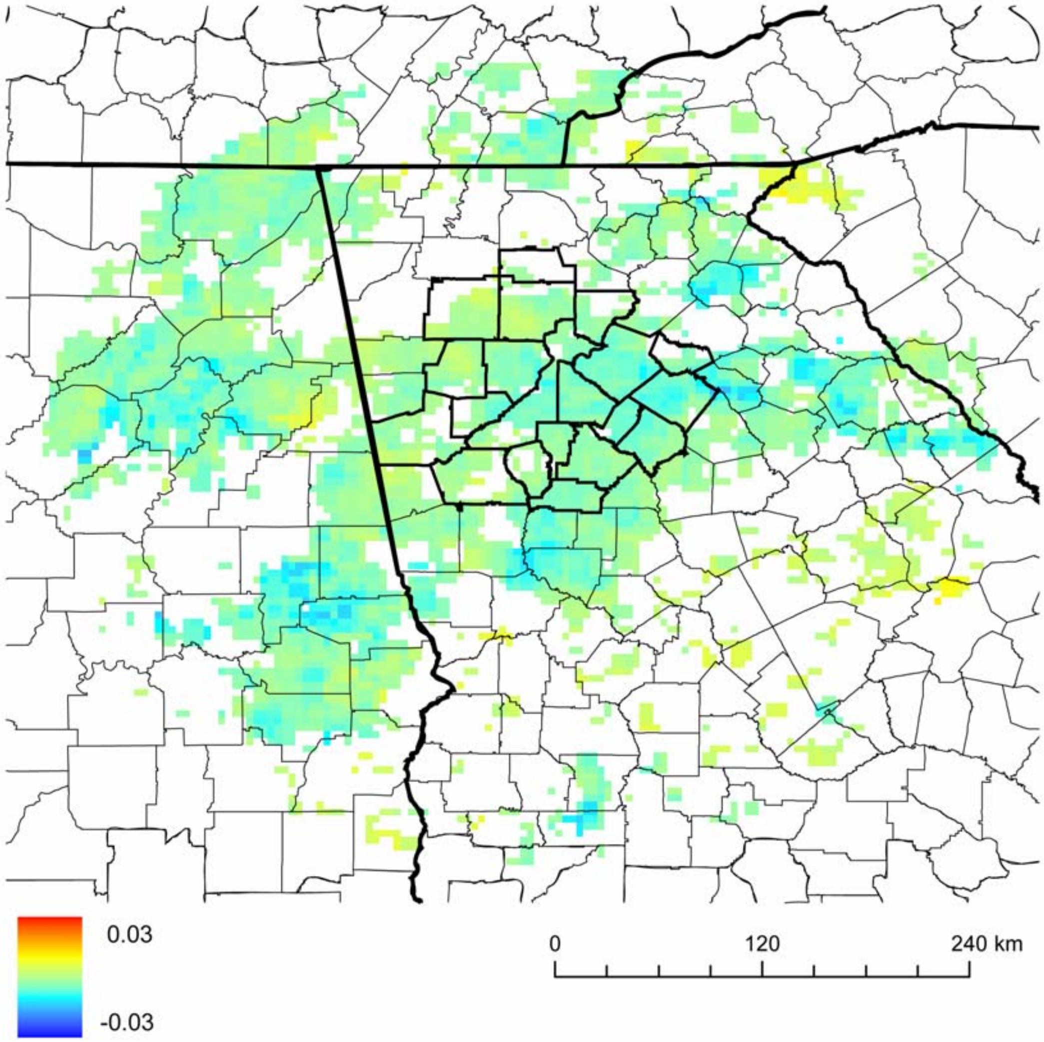


Figure 4.3.10. Sunday minus Monday difference map of mean precipitation amounts (mm/radar scan). Only significant grid points at the 95% confidence level are shown.

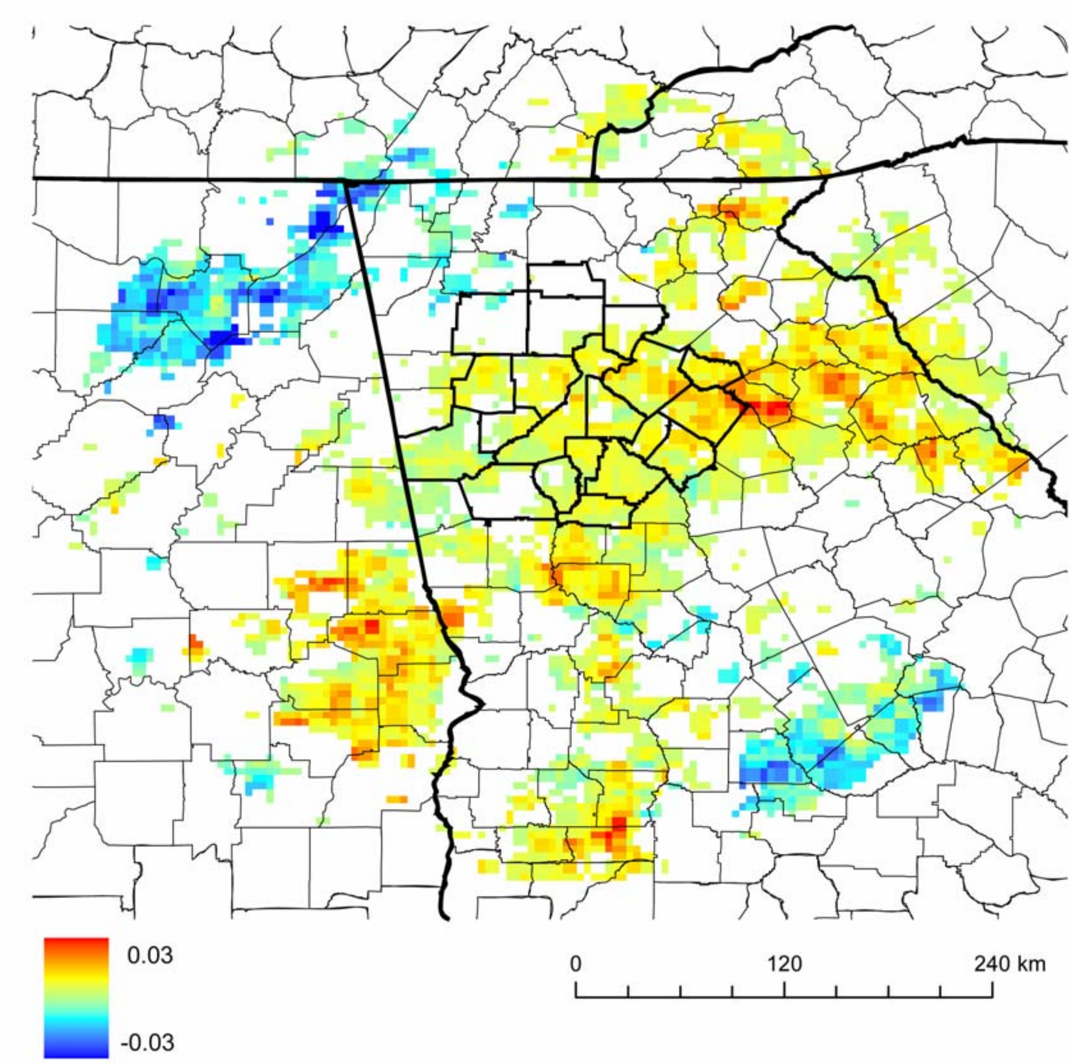


Figure 4.3.11. Same as Figure 4.3.9, except for Monday minus Wednesday.

Some of the statistical tests showed a pattern of significant p-values from the far western to far eastern sections of the metro-Atlanta area. The comparisons showing this spatial pattern are: Thursday with Saturday (Figure 4.3.12), Thursday with Friday (Figure 4.3.13), Wednesday with Thursday (Figure 4.3.14), and Sunday with Thursday (Figure 4.3.15). Each of these figures showed a stretch of significantly higher precipitation amounts fell on Thursdays from Paulding County straight east to Walton County.

This area is also of interest when examining the mean precipitation measurements on Thursday (Figure 4.3.2), where the central portion of the metro area has the highest precipitation amounts when compared to the rest of the urban and surrounding rural areas. This central area included the heart of the metro area and downtown Atlanta. When examining the PM 2.5 concentrations by day of the week, Thursday had the highest average and median values at two of the three EPA stations (Decatur and Doraville). This may indicate that when there are large amounts of PM 2.5 present within the central areas in Atlanta's metro area on Thursdays, it influences cloud microphysics and creates a significant increase in the amount of precipitation that falls across the entire center area of Atlanta, both due west and due east of the city's hub.

4.4 Analysis of PM 2.5 Concentrations and Precipitation Amounts

PM 2.5 concentrations at the three metropolitan Atlanta EPA stations were stratified into two categories. Days were classified as high aerosol days when the daily average concentration was above one-half the standard deviation (12 days) and low aerosol days when the daily average concentration was below negative one-half the standard deviation (15 days) (Table 4.1.1). Both sets of days were further stratified by the presence of a MT air mass in Atlanta

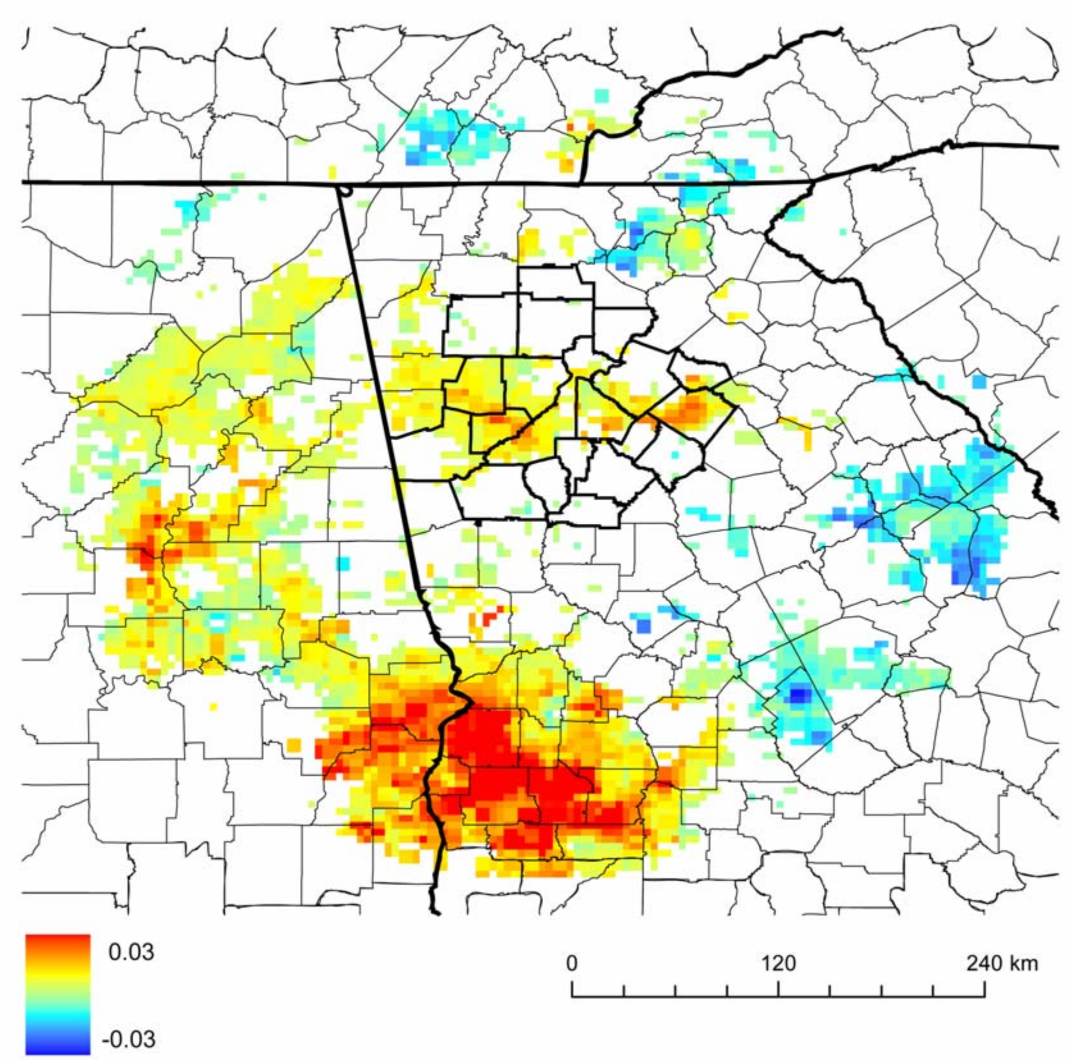


Figure 4.3.12. Same as Figure 4.3.9, except for Thursday minus Saturday.

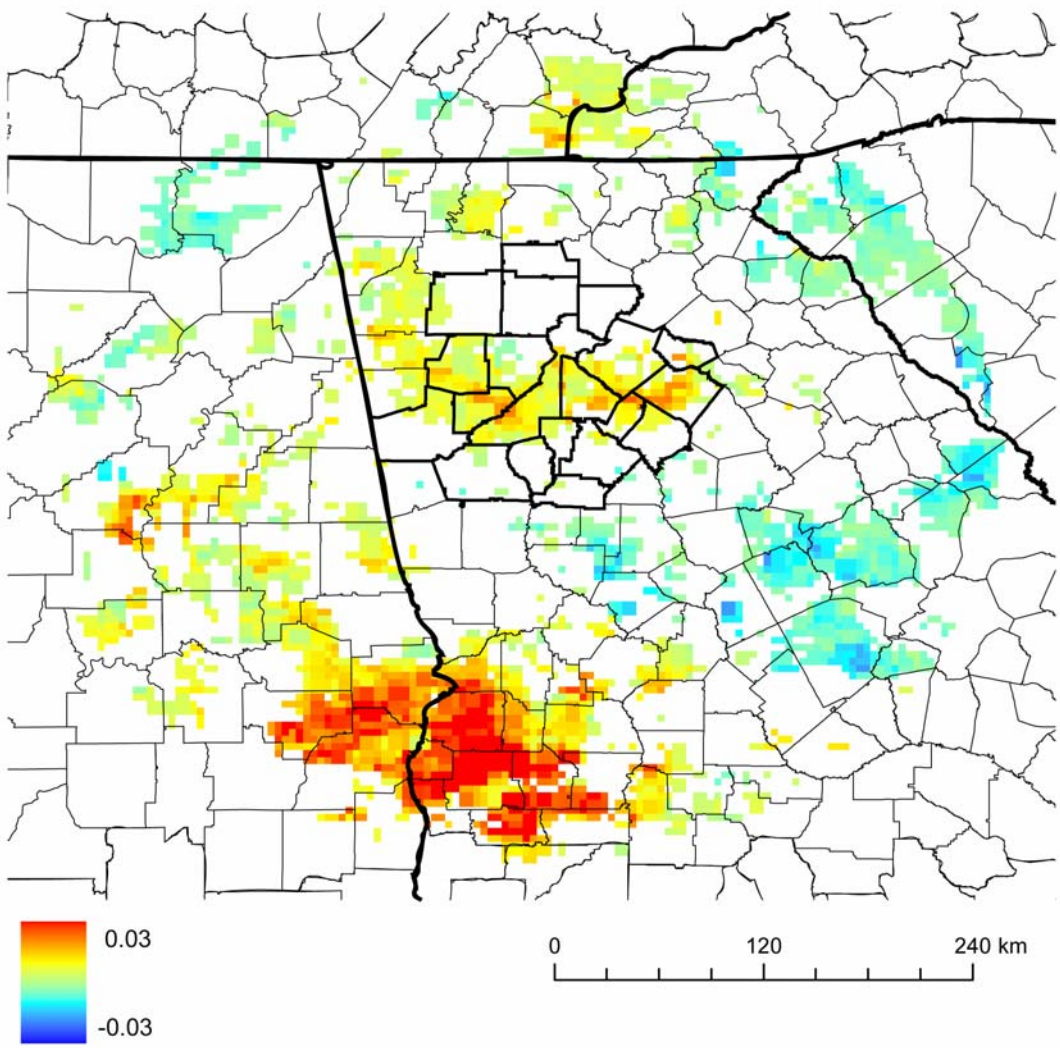


Figure 4.3.13. Same as Figure 4.3.9, except for Thursday minus Friday.

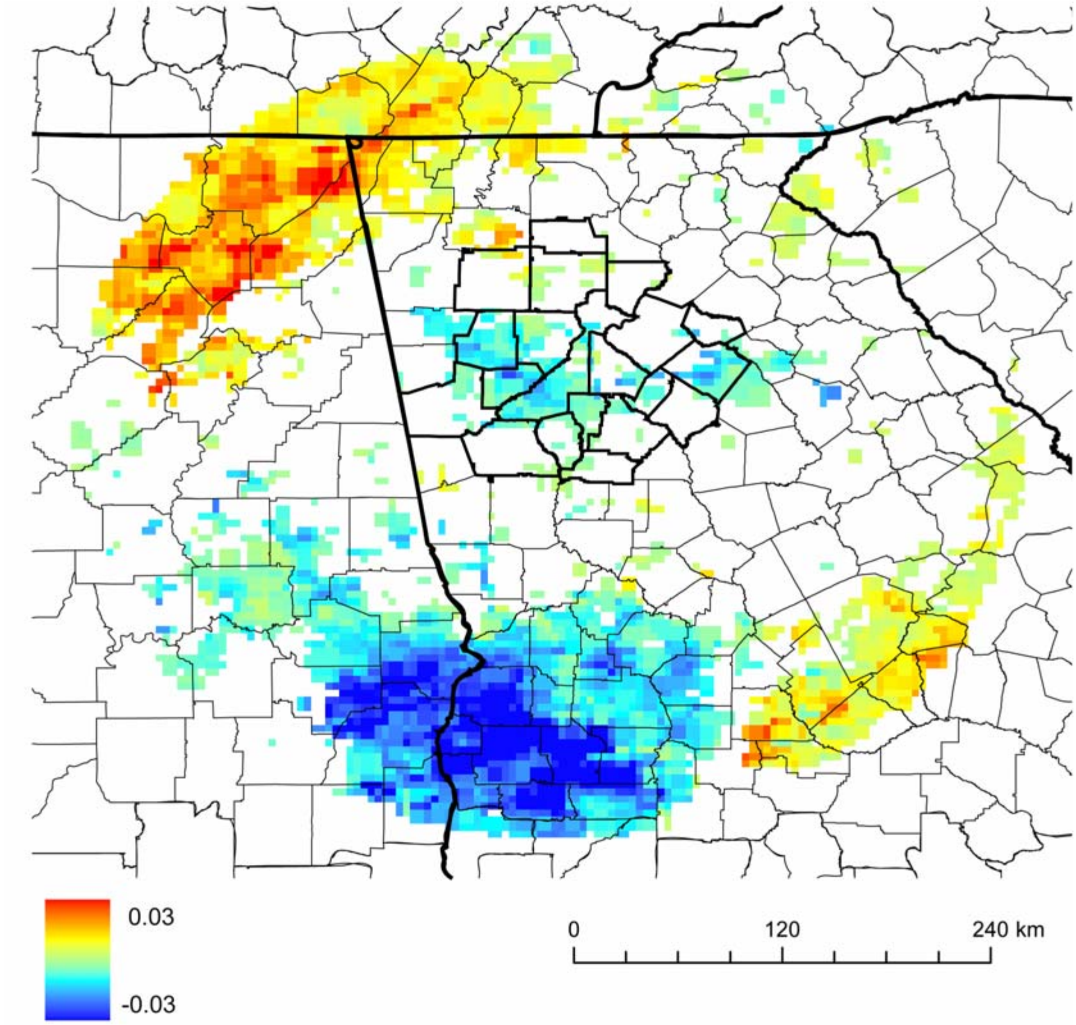


Figure 4.3.14. Same as Figure 4.3.9, except for Wednesday minus Thursday.

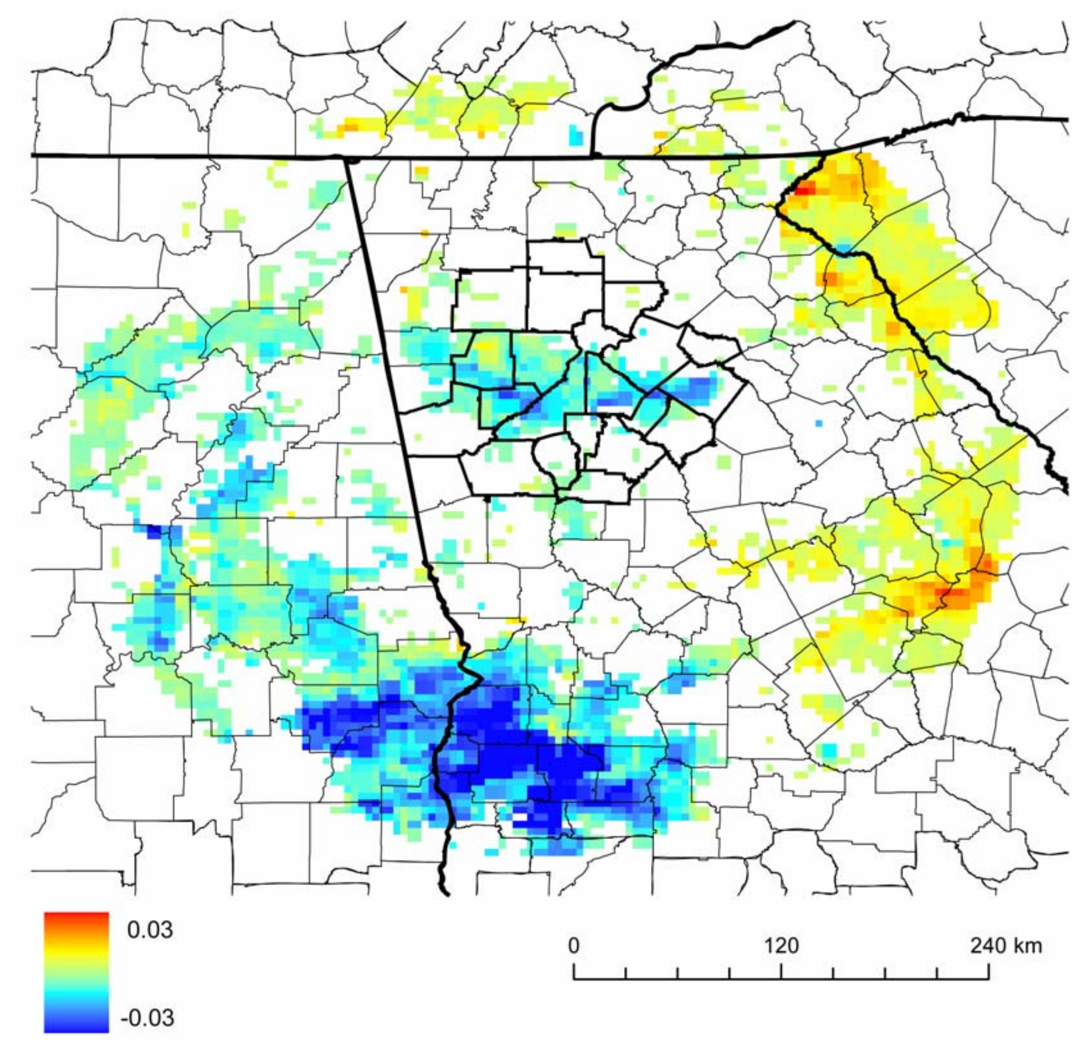


Figure 4.3.15. Same as Figure 4.3.9, except for Sunday minus Thursday.

Table 4.4.1. Dates of high and low aerosol days.

High Aerosol Days	Low Aerosol Days
2003 June 25	2003 June 11
2003 June 26	2003 June 15
2003 July 18	2003 July 9
2003 July 19	2003 July 13
2003 July 20	2003 August 14
2003 August 10	2003 August 29
2003 August 17	2003 August 30
2003 August 18	2003 August 31
2003 August 19	2004 June 16
2003 August 20	2004 June 17
2004 July 22	2004 June 18
2004 July 25	2004 June 22
	2004 July 7
	2004 July 26
	2004 August 3

during the summers of 2003-04. Appendix A shows the frequency count of radar scans and percent of total radar scans by hour for high and low aerosol days (Table A.2). Again, no observed bias was found that would greatly affect the results.

Precipitation amounts were analyzed over the metro-Atlanta region for both high and low aerosol days. Mean precipitation amounts were found throughout the metro-Atlanta area for high aerosol days (Figure 4.4.1), where Bartow, Paulding, Cobb, and central Walton Counties had the highest average rainfall amounts. These areas of higher averages coincided with locations that had larger frequency counts of precipitation accumulation (Figure 4.4.2). On low aerosol days, the highest average precipitation totals occurred in southern Coweta and most of the eastern area of metro-Atlanta, specifically Newton and southern Walton Counties (Figure 4.4.3). When comparing this observation to the number of times any accumulated precipitation was recorded, the higher average rainfall totals were in similar areas to the larger counts of rainfall occurrence in Newton and Walton Counties (Figure 4.4.4). This was not the case in Coweta County where there were fewer observations of rainfall events and fewer, more intense events occurring at this location than in Newton and Walton Counties.

Figure 4.4.5 shows a difference map between high aerosol and low aerosol day precipitation means for each grid cell. Higher mean rainfall amounts occurred on high aerosol days for most of the metro area, especially over Bartow, Paulding, Cherokee, Cobb, Douglas Counties and central Walton Counties. However, higher mean rainfall amounts occurred on low aerosol days in Newton, Henry, Fayette, and southern Coweta Counties in the southeast. Figure 4.4.6 is a difference map between the high aerosol day counts and the low aerosol day counts. This figure shows more occurrences of precipitation accumulation during the high aerosol days in the northwest portion of the metro-Atlanta area than on low aerosol days. On the other hand, the southeast section of metro-Atlanta had a higher number of precipitation occurrences on low aerosol days.

A statistical analysis was done using the Wilcoxon signed-ranks test in order to see if there was a significant difference in average precipitation amounts between high and low aerosol days. Figure 4.4.7 is a map of p-values for each grid point. The null hypothesis assumes that high and low aerosol days are not different from one another. The alternative hypothesis rejects the null hypothesis and presumes that the two sets of days are from separate and distinct populations. A large amount of the metro-Atlanta area showed p-values near zero, which means that the null hypothesis of no effect can be rejected and that the difference in average precipitation totals between high and low aerosol days was significant. Conversely, when comparing high and low aerosol days in the southeast portion of the metro area (i.e., Fayette, Clayton, DeKalb, southern Gwinnett and Walton, Rockdale, Newton, and Henry Counties), there

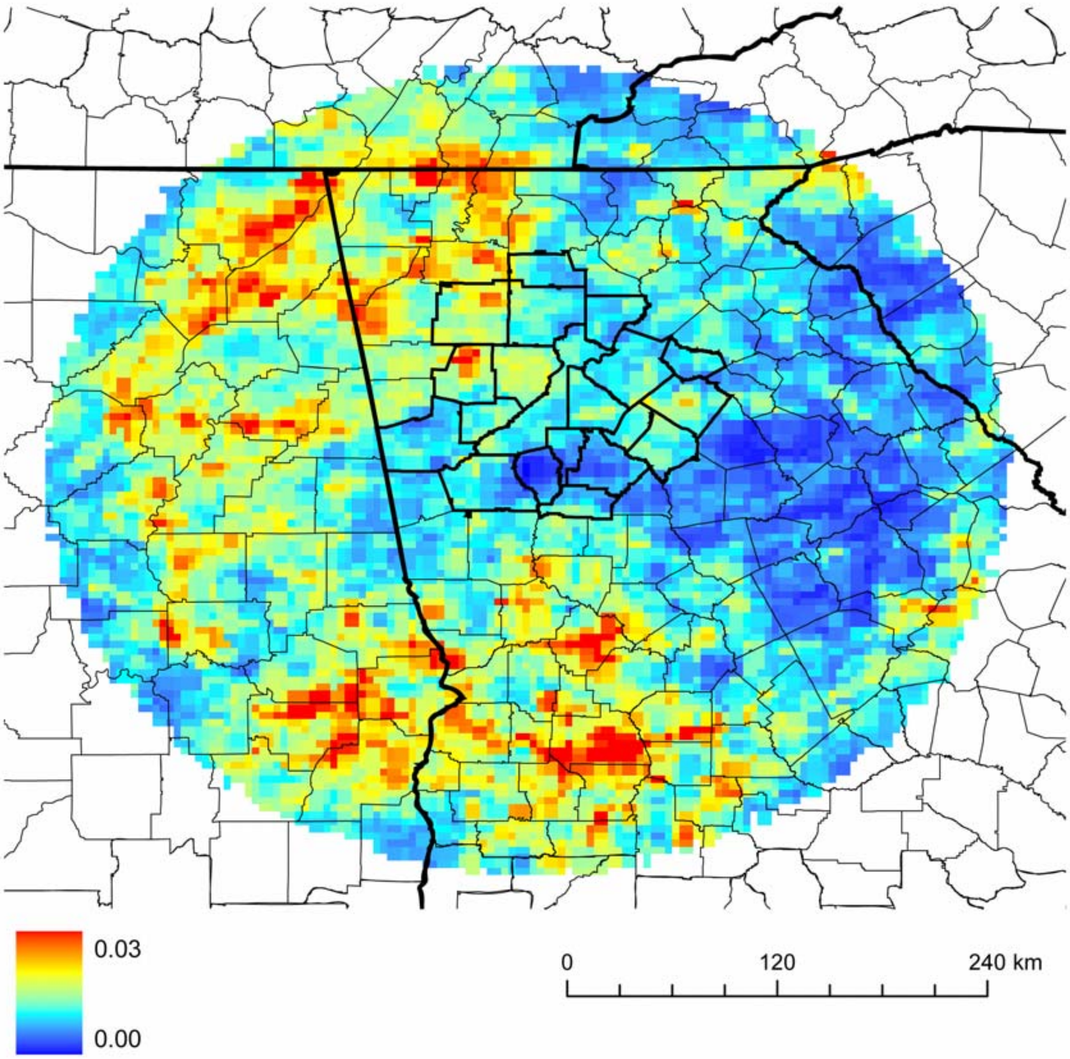


Figure 4.4.1. Mean precipitation amounts (mm/radar scan) on high aerosol days with a MT air mass present over Atlanta during the summer months (June-August) of 2003-04.

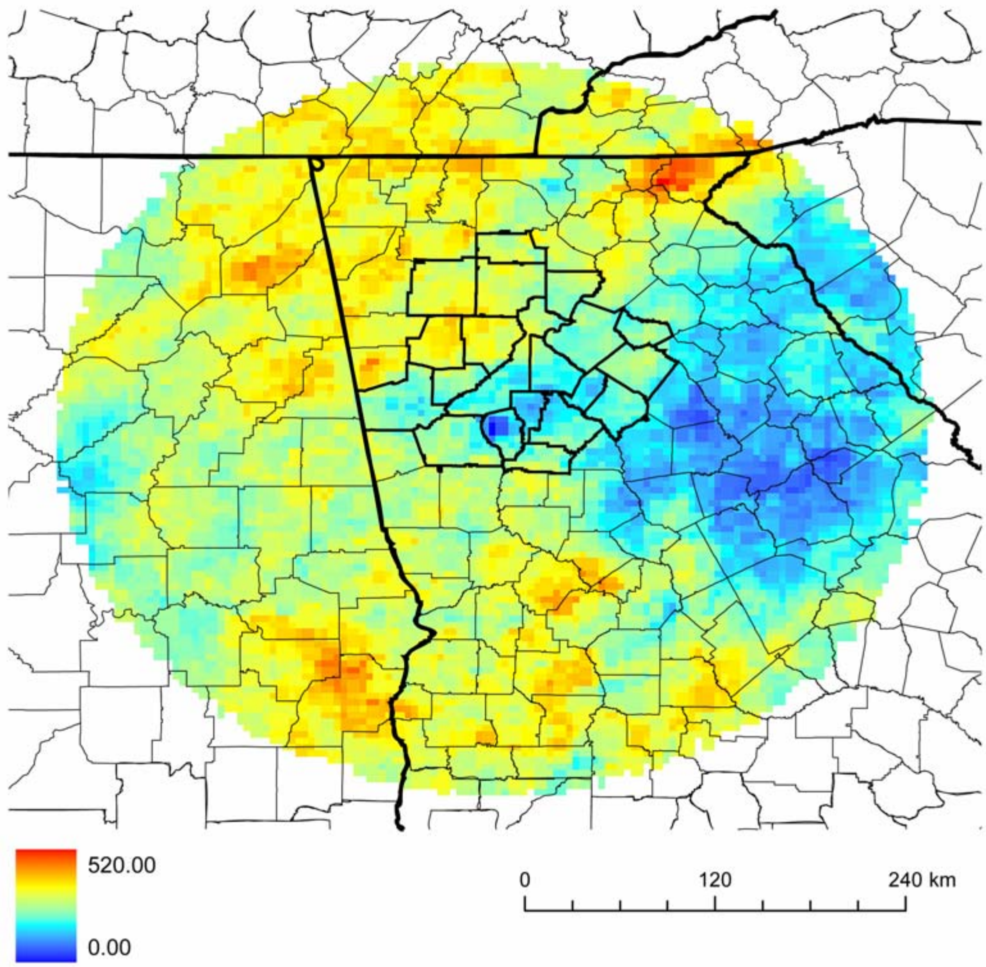


Figure 4.4.2. Frequency count of radar scans with precipitation accumulation on high aerosol days with a MT air mass present over Atlanta during the summer months (June-August) of 2003-04.

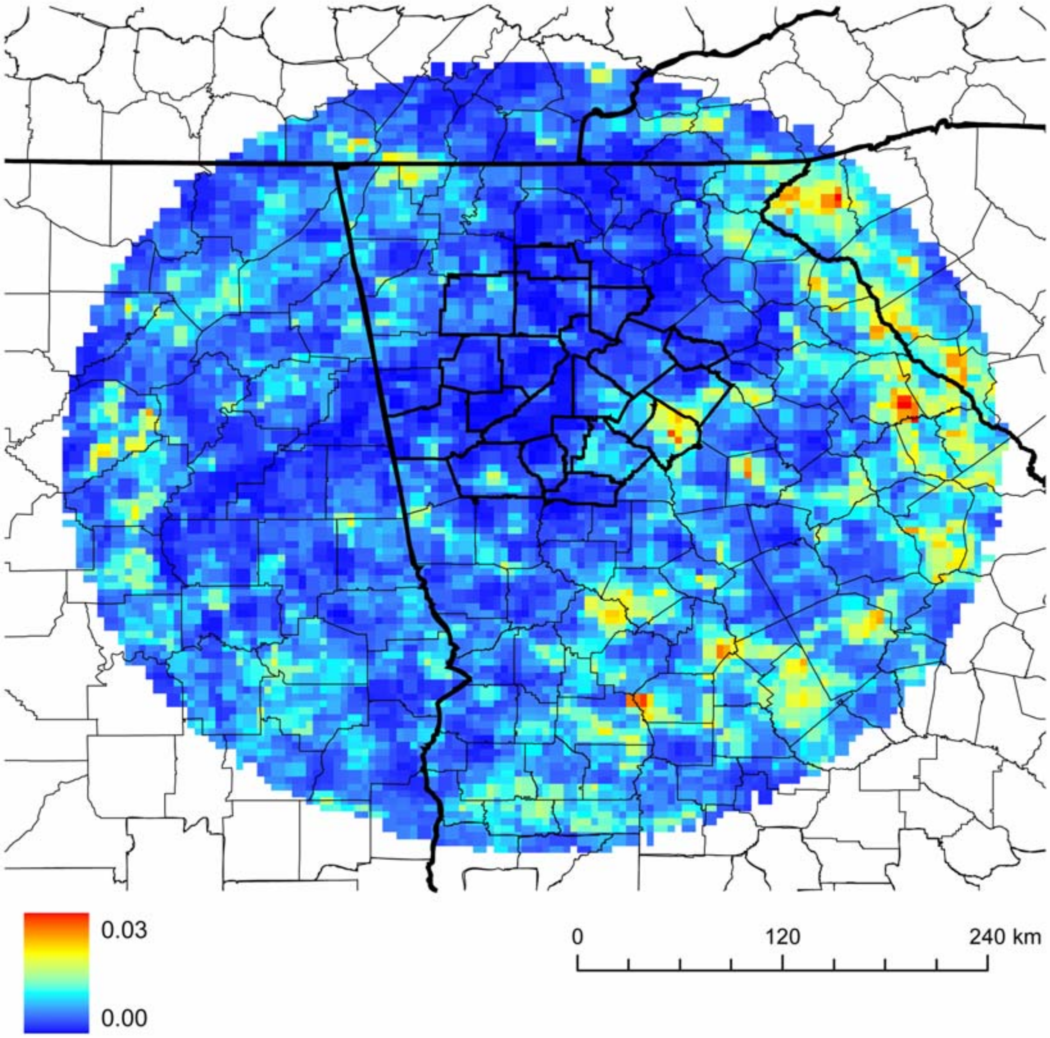


Figure 4.4.3. Same as Figure 4.4.1, except for low aerosol days.

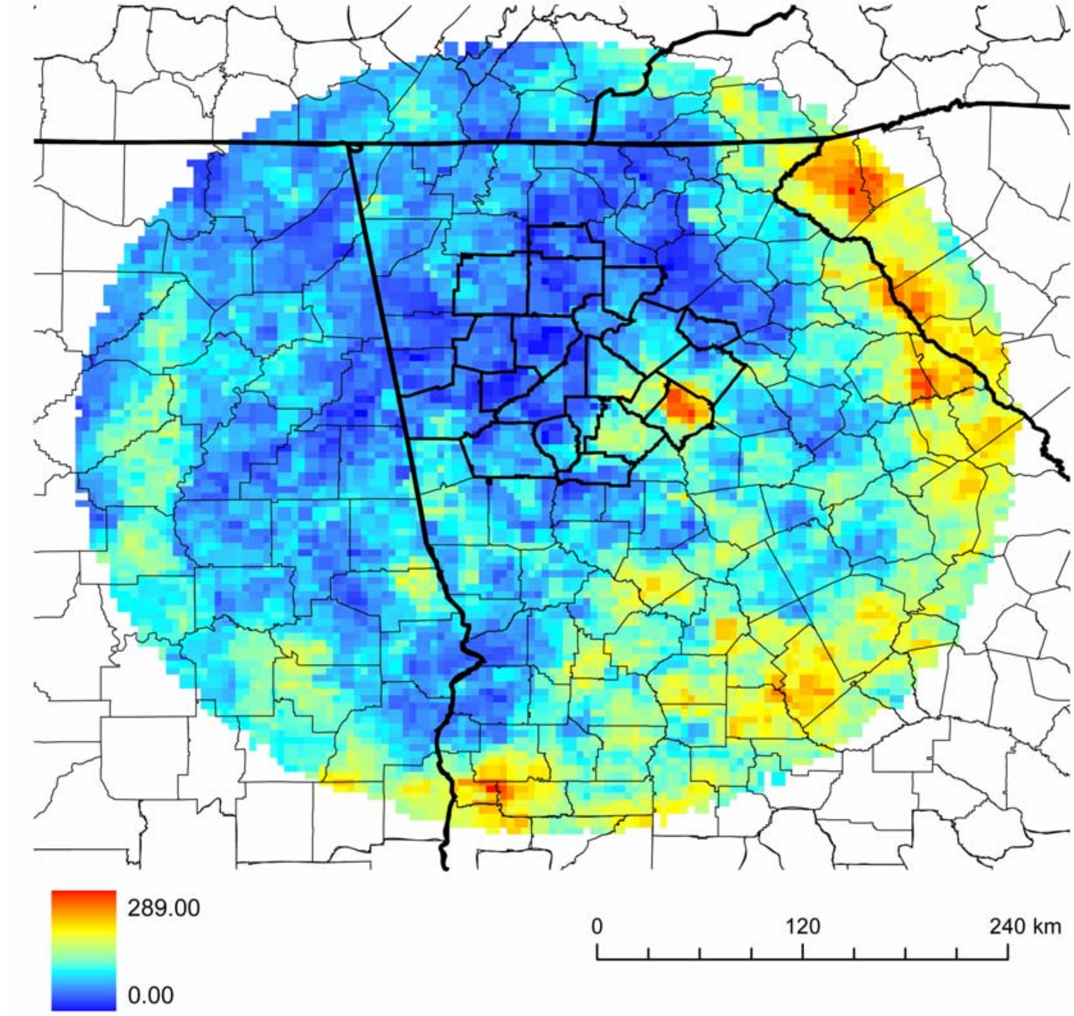


Figure 4.4.4. Same as Figure 4.4.2, except for low aerosol days.

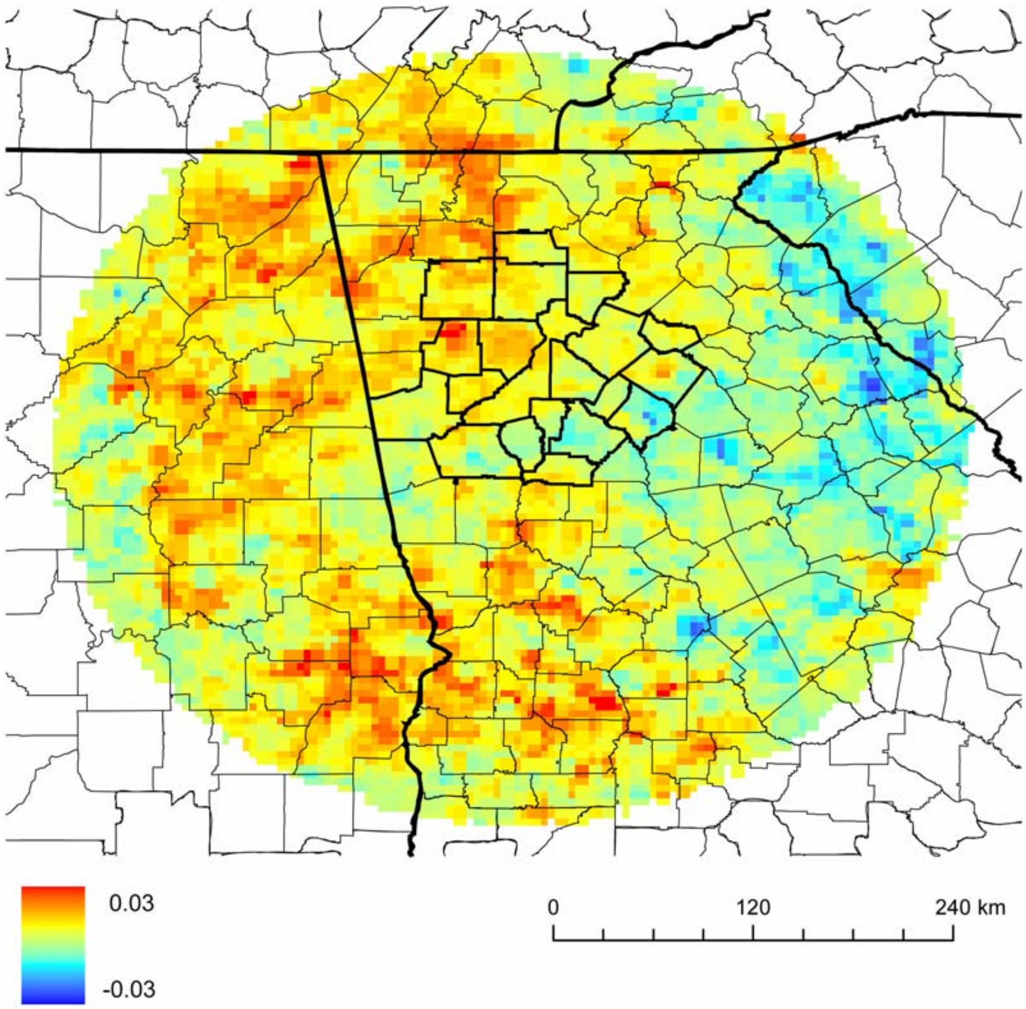


Figure 4.4.5. High minus low aerosol days difference map of average precipitation amounts (mm/radar scan).

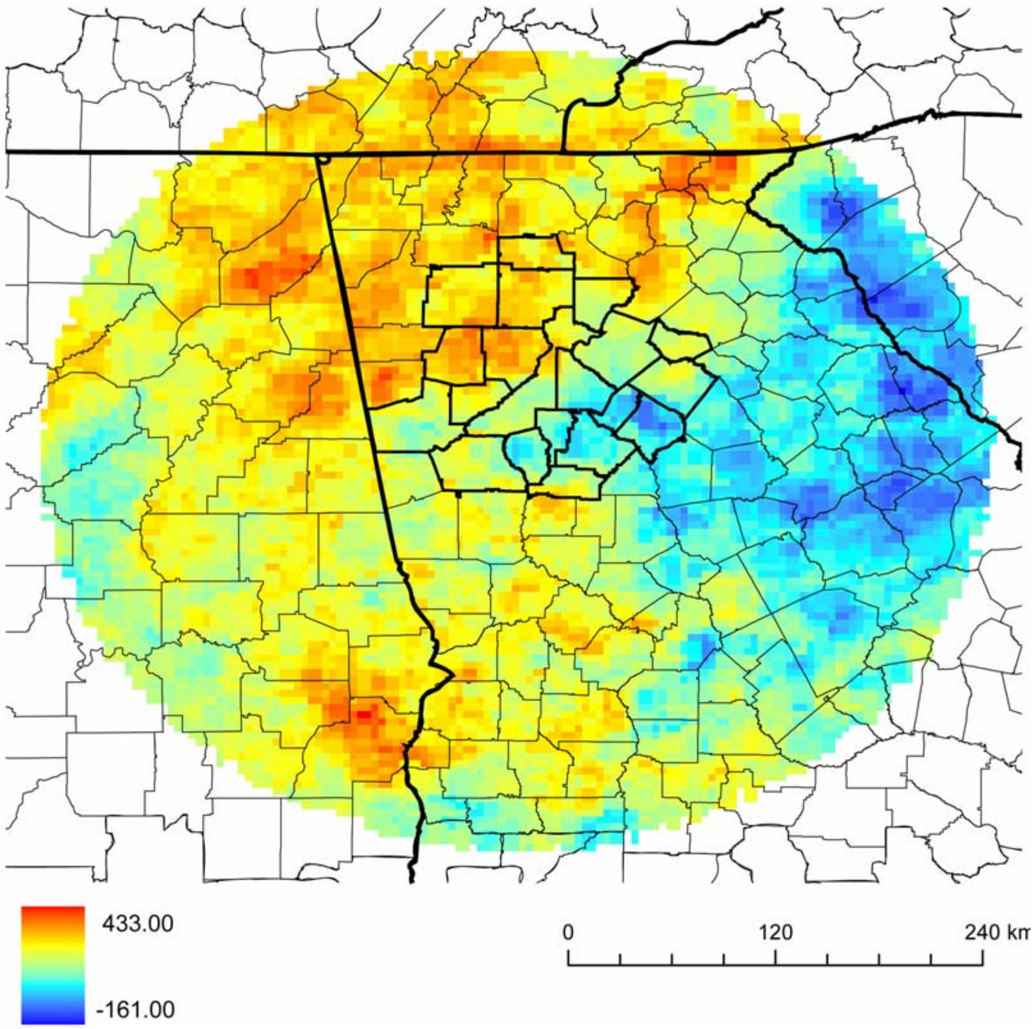


Figure 4.4.6. High minus low aerosol days difference map of the frequency count of radar scans with precipitation accumulation.

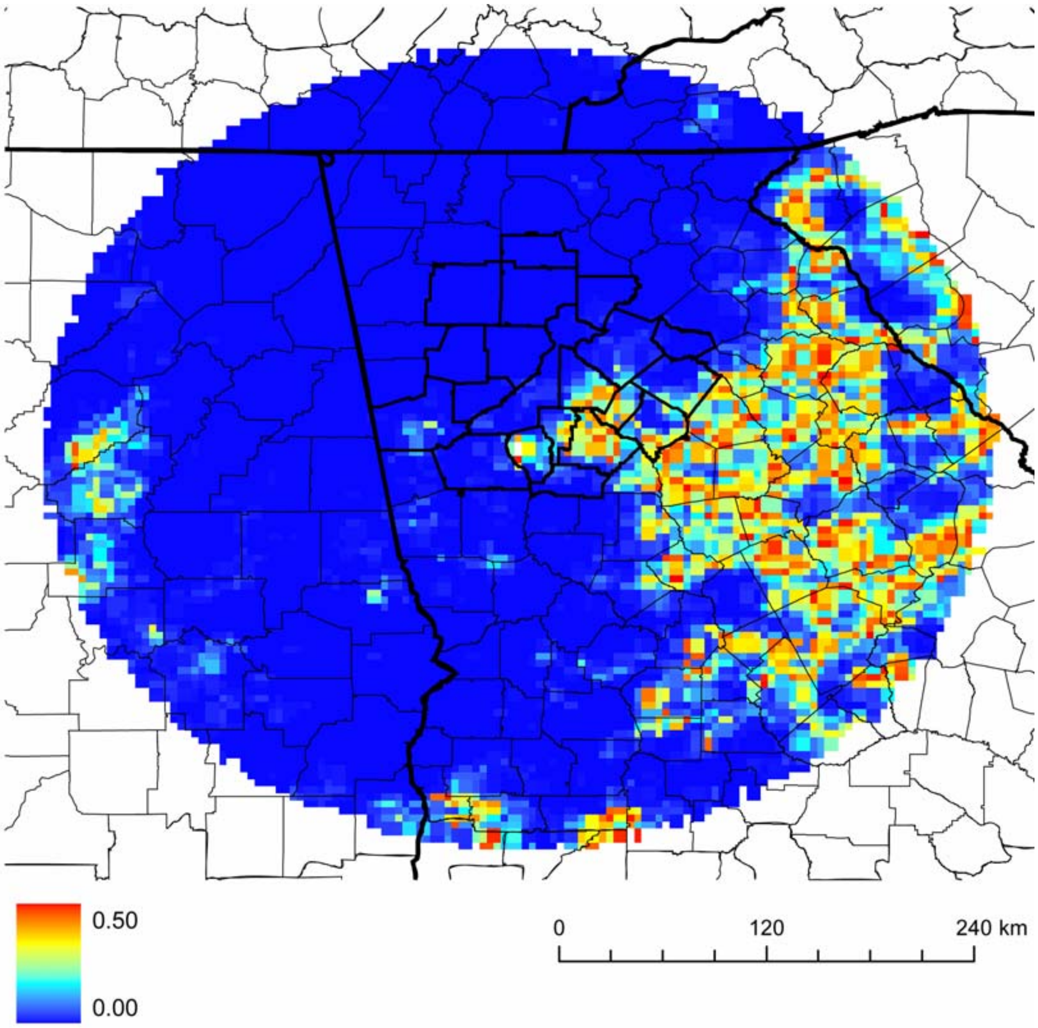


Figure 4.4.7. P-values from a Wilcoxon signed-ranks test comparing high and low aerosol days at the 95% confidence level.

was no statistically significant difference between the two sets of days.

4.5 Synoptic Analysis

Understanding the prevailing meteorological conditions can assist in the explanation of the findings of PM 2.5 concentrations and precipitation amounts for this study discussed in section 4.4. One such valuable tool was the skew-T diagram to understand the stability of the atmosphere. KFFC radiosonde observations were examined and assumed to be representative of the Atlanta area. Analysis of daily weather maps provided a better and more complete understanding of synoptic surface and upper air features that contribute to the weather in Atlanta on a regional scale. Skew-T log-P diagrams along with daily weather maps were used to understand any differences in the synoptic-scale environment on high versus low aerosol days.

4.5.1 Skew-T Diagrams

Skew-T log-P diagrams were available for all low aerosol days (15 days) and all but one day high aerosol days (12 days) at 1200 UTC from KFFC. The use of convective available potential energy (CAPE) and convective inhibition (CIN) are good measurements for understanding how unstable the atmosphere is and how much energy is needed to initiate convection, respectively (Tables 4.5.1 and 4.5.2). Higher CAPE values indicate an unstable atmosphere and a higher CIN indicates a stronger cap that would inhibit the formation of convection. The mean and median CAPE and CIN values were calculated from the skew-T diagrams on high and low aerosol days (Table 4.5.3). One value for CIN was eliminated from analysis for one high aerosol day because the improbability of such a value (59188 J kg^{-1}). On

Table 4.5.1. Stability associated with values of Convective Available Potential Energy (CAPE). From Melbourne, FL National Weather Service Forecast Office (2007).

CAPE Value (J kg^{-1})	**Atmospheric Condition**
0-1000	Marginally unstable
1000-2500	Moderately unstable
2500-3500	Very unstable
>3500	Extremely unstable

Table 4.5.2. Stability associated with values of Convective Inhibition (CIN). From Melbourne, FL National Weather Service Forecast Office (2007).

CIN Value (J kg^{-1})	**Atmospheric Condition**
<15	Fair weather cumulus field (Weak Cap)
15-50	A few strong thunderstorms may form is CIN is overcome (Weak Cap)
50-150	Strong thunderstorms may form if CIN is overcome (Moderate Cap)
>200	Thunderstorm development unlikely (Strong Cap)

high aerosol days that were analyzed, the mean and median CAPE values were 890 J kg^{-1} and 875 J kg^{-1}, respectively. The mean convective inhibition (CIN) was 75 J kg^{-1} and the median CIN was 73 J kg^{-1}. For low aerosol days, the mean CAPE was 457 J kg^{-1} and the median 277 J kg^{-1}. The mean CIN was 118 J kg^{-1} and the median 129 J kg^{-1}.

CAPE was found to be higher on high aerosol days. Among the CAPE values, four were above 1000 J kg^{-1}, while only two CAPE values on low aerosol days were above this value. CIN values were higher on low aerosol days. These values indicate that high aerosol days have less of a cap to inhibit convection along with more convective energy in order for convection to develop over the Atlanta area. When this finding was compared to the difference map of precipitation amounts (Figure 4.4.5) and frequency counts (Figure 4.4.6) between high and low

Table 4.5.3. Mean and median CAPE and CIN values for high and low aerosol days. All values are in J kg^{-1}.

	Mean CAPE	Median CAPE	Mean CIN	Median CIN
High Aerosol Days	890	875	75	73
Low Aerosol Days	457	277	118	129

aerosol days, most of the metro area, except the southeastern counties where it was not significant, showed higher precipitation amounts and frequency counts of precipitation on high aerosol days.

The mixing level of the atmosphere extends to approximately 1 km above the surface. This area of the atmosphere is important to observe because when an inversion develops, it is the top of the layer in which pollution is well mixed, above which there is little or no pollution (Scorer 2002). This level is where the vertical transport of moisture and wind show relatively little change with height (Wallace and Hobbs 1977). The higher the mixing level, the more aerosols disperse throughout the atmosphere. One would assume that on a low aerosol day, the mixing level height would be larger than that on a high aerosol day. Analysis of the mixing levels on high and low aerosol days did not show any large differences in these heights. High aerosol days showed mixing level heights up to or slightly *below* 950 hPa. Low aerosol days showed the mixing levels to extend up to or slightly *above* 950 hPa. However, the mixing level heights of high and low aerosol days are not too different from one another.

As noted previously, the mixing layer is located below an inversion. If a low inversion is present, the pollution released into the atmosphere, from its source, will distribute in area linearly and grow sideways (Figure 4.5.1). It will not grow upwards because of the mixing layer beneath

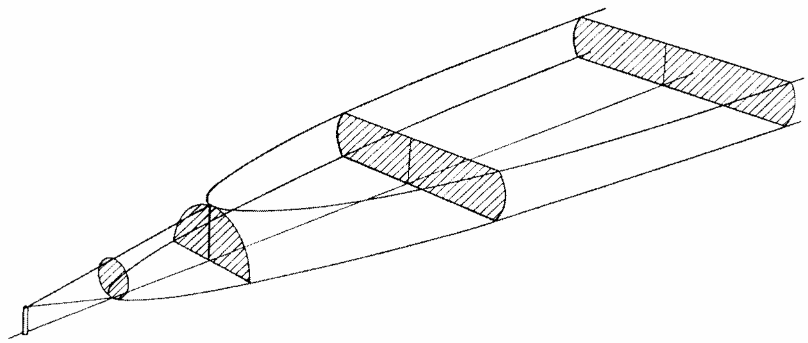


Figure 4.5.1. Distribution of pollution under a low inversion top. From Scorer 2002.

the inversion. When looking at the average precipitation amounts on high aerosol days (Figure 4.4.1) and the difference maps of counts and means between high and low aerosol days (Figures 4.4.5 and 4.4.6), a fan-shaped pattern developed east of the urban area. One would then assume that this fan-shaped pattern was due to shallower mixing levels on high aerosols days. However, this exact area had no significant difference in precipitation amounts between the two sets of days (Figure 4.4.7).

4.5.2 Daily Weather Maps and Wind Roses

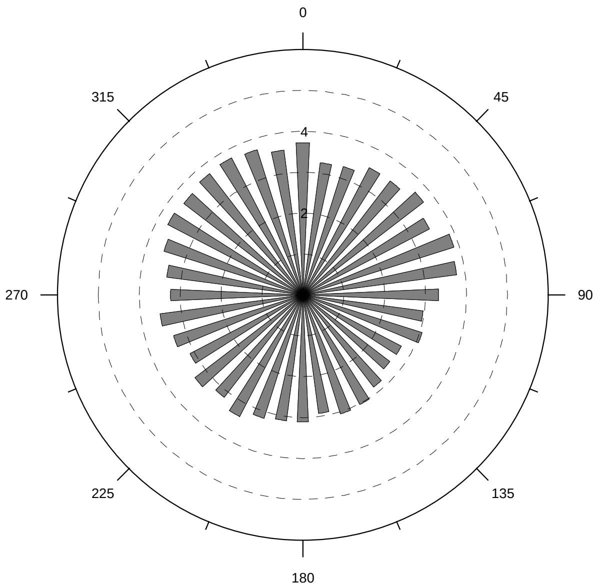
Daily weather maps consisted of surface and 500 hPa maps at 1100Z of each day, precipitation maps for 24-hr accumulations ending at 1100Z, and daily maximum and minimum temperatures for the given day. Wind roses from the Hartsfield-Jackson International Airport in Atlanta are shown in Figure 4.5.2 with average wind speeds and directions for high and low aerosol days and all other days. The days not classified as high or low aerosol days (Figure 4.5.2a) showed consistent wind speeds for each direction.

On high aerosol days, surface maps show high pressure dominating the southeastern

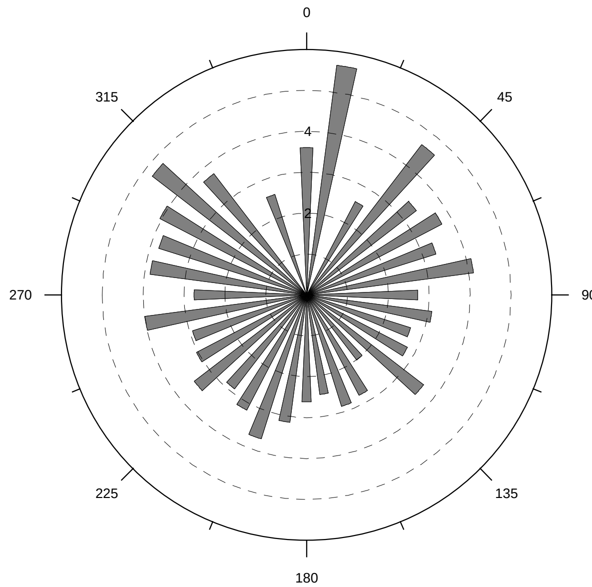
United States. More often than not, centers of low pressure were located in the Plains and Great Lakes regions. The wind rose for high aerosol days (Figure 4.5.2b) did not have any wind direction show dominantly higher average wind speeds. This showed that wind direction did not have an effect on aerosol concentrations. Precipitation maps showed little or no rainfall accumulations across the Atlanta area for the previous 24 hours. The 500 hPa maps showed that winds were quite slow (≤ 7.7 m s^{-1}) from varying directions for each high aerosol day. Most days showed the metro-Atlanta region to be either under an upper-level ridge that spanned across the middle and southeastern sections of the United States or south of an upper-level trough. This was concurrent with Atlanta area maximum temperatures dominantly in 26.7-31.7º C range, with a swell of temperatures above 32.2º C north and west into the Midwest and Plains regions.

Surface maps for the low aerosol days indicated the presence of high pressure systems in the southeast and off the eastern coast of the United States. One interesting finding was that three days had a tropical system present in either the Gulf of Mexico (2 different tropical storms) or on the mid-Atlantic coast (1 hurricane). The wind rose for low aerosol days (Figure 4.5.2c) showed a preference for higher average wind speeds from westerly and easterly directions. However, there did not appear to be a strong preference for any one direction and showed wind direction to not have an effect on PM 2.5 concentrations. The 500 hPa maps showed wind speeds to be a bit faster (≤ 10.3 m s^{-1}) than on high aerosol days with directions primarily from a westerly direction. Low aerosol days showed that upper-level flow tended to be a little more zonal than meridional when compared to high aerosol days. Many days also showed an upper-level high pressure located off the eastern coast of the United States.

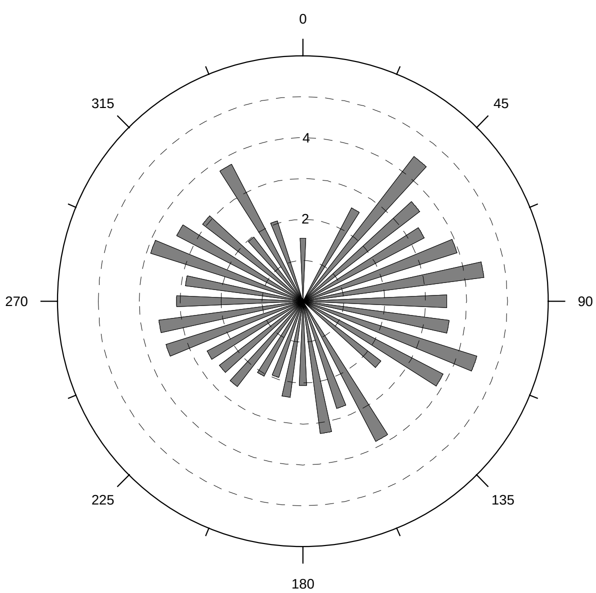
The previous 24-hr precipitation maps showed that every single low aerosol day over the metro-Atlanta area had some measurable amount of rain. This is of great importance because it



(a)



(b)



(c)

Figure 4.5.2. Wind roses for Atlanta, GA, at the Hartsfield-Jackson International Airport that indicate the average wind speed (m s^{-1}) along the radial axis and the wind direction in degrees degrees is on the angular axis for a) neither high or low aerosol days, b) high aerosol days, and c) low aerosol days.

gives an explanation of why there were lower aerosol values on these particular days. The precipitation that fell on the previous day may have washed out many of the aerosols that were present over the Atlanta area.

4.6 Summary

Precipitation amounts and frequencies from WSR-88D radar were analyzed with 2.5 μm particulate matter (PM 2.5) concentrations for Atlanta, GA, during June, July, and August of 2003-04. Both data sets were analyzed on days when a MT air mass resided in Atlanta this air mass was found to be present for 44% of those days. These days had the largest precipitation amounts and frequency counts in the northwest and east sections of the metropolitan area. Two of three United States Environmental Protection Agency aerosol observing stations (Decatur and Doraville, GA) showed a peak in PM 2.5 on Thursdays. This is of interest because Thursday precipitation amounts were significantly higher when compared to most other days of the week (Sunday, Wednesday, Friday, and Saturday). This pattern was found across the central portion of metro-Atlanta.

Precipitation amounts were also analyzed on high and low aerosol days (days one-half above or below the standard deviation, respectively). The synoptic analysis showed high aerosol days under a 500 hPa ridge or south of an upper-level trough and low aerosol days had a 500 hPa high pressure located off the eastern coast of the United States. Average precipitation amounts were greater on high aerosol days throughout most of metro-Atlanta with greater average amounts on low aerosol days in the southeast metro area. Statistically significant differences in precipitation amounts were found for most of the metro area. However, the southeastern counties were found to not have significant precipitation amounts between high and low aerosol days. Greater instability was present on high aerosol days (higher average CAPE values and lower average CIN values) when mixing depths were shallower. Low aerosol days were typically preceded by precipitation accumulations the previous 24 hours, which could explain the reasoning for the lack of aerosols.

CHAPTER 5

CONCLUSIONS

This thesis examined the role of aerosols in Atlanta, GA, on summer precipitation. The referred literature demonstrates that the amount of pollution in the atmosphere over an urban area is typically higher on weekdays (Monday-Friday) when compared to the days on the weekend (Saturday and Sunday). Recent work by Bell et al. (2007) showed that aerosol pollution affected precipitation. The southeast United States showed statistically significant increases in precipitation during the week when aerosol concentrations were the greatest. However, past research has not provided a definitive explanation of what role urban aerosols play in enhancing or inhibiting precipitation.

This study examined whether there was a weekly cycle in pollution and precipitation amounts. Only days when a maritime air mass (MT) was present in the city of Atlanta were analyzed in order to assure that convection was forced by the urban area. The summer months of June, July, and August for the 2003-04 were observed.

This work addressed previous suggestions (Lowry 1998; Shepherd 2005) of urban effects on precipitation by using a synoptic stratification (i.e., MT days), using small and temporally short experimental units when observing rainfall amounts (i.e., by day of the week and by high and low aerosol days), and introducing new observational methods for measuring rainfall (i.e., surface-based radar estimates).

5.1 Precipitation and Day of Week

Daily aggregated maps were created for the summers of 2003-04 when a MT air mass was present in Atlanta. This research provided some indication that there may be a weekly cycle in precipitation with apparent smaller average precipitation amounts on the weekends when compared to weekdays. Monday and Thursday were shown to have the highest average precipitation amounts across the metro-Atlanta area. Monday's highest average amounts occurred in the eastern half of the metro area and Thursday showed the largest average totals to be in a linear manner across the interior metro area. The southern part of the metro area showed a smaller average precipitation amount on all MT days and was reflected in each daily average precipitation amount.

A Wilcoxon signed-ranks test was performed on pairs of days to see if there was any statistically significant difference in means. Two pairs of days, Sunday with Monday and Monday with Wednesday, showed almost the entire metro-Atlanta region, except for a small area in the southwest, had significantly higher precipitation amounts on Monday. However, one of the largest findings of this thesis was that Thursdays continuously showed a considerable dissimilarity when compared to other days of the week. When Thursday was compared to Sunday, Wednesday, Friday, and Saturday a similar pattern was found. Statistically significant greater precipitation amounts occurred on Thursday from Paulding County straight east through downtown Atlanta to Walton County. This showed that Thursday had a significantly different amount of precipitation that fell over the mid-section of the metro-Atlanta area.

5.2 Precipitation and Aerosols

The Thursday observation of higher average rainfall amounts throughout the center portions of the Atlanta-metro area was also concurrent with the Decatur and Doraville EPA stations showing Thursday to have the highest average PM 2.5 concentrations. This perhaps shows that on Thursdays when there are large amounts of PM 2.5 concentrations present within the central areas in Atlanta's metro area, it leads to a significant effect on the amount of precipitation that falls across the entire center area of Atlanta, both due west and due east of the urban center. Tuesday's and Thursday's higher average PM 2.5 concentrations could be due to a weekly peak in the release of aerosols from traffic and industrial facilities.

Days with a MT air mass present in Atlanta were aggregated by high and low aerosol days. High aerosol days had the highest mean precipitation amounts located in the northwestern and eastern areas of metro-Atlanta. Low aerosol days had the highest average total precipitation in southern Coweta and the eastern metro area. Difference of means maps indicated that higher mean rainfall amounts took place on high aerosol days for Bartow, Paulding, Cherokee, Cobb, Douglas Counties and central Walton Counties (mostly all in the northwest). Higher mean rainfall amounts occurred on low aerosol days in Newton, Henry, Fayette, and southern Coweta Counties (mostly all in the southeast). Analysis of precipitation amounts between high and low aerosol days showed a significant difference over a large extent of Atlanta's urban area except for the southeast.

5.3 Meteorological Effects

Analysis of skew-T diagrams on high aerosol days showed the mixing level up to or slightly below 950 hPa and up to or slightly above 950 hPa on low aerosol days. High aerosol days were found to have greater instability when comparing convective available potential energy (CAPE) and convective inhibition (CIN) values. Analysis of the weather maps at 500 hPa showed most high aerosol days had weak upper level winds and an upper-level ridge spanning across the middle and southeast sections of the United States. Both the lower mixing layer height and general subsidence over the metro-Atlanta area gave explanations for the days defined as having a high aerosol content. Precipitation accumulations the previous 24 hours of low aerosol days explained the lack of aerosols that were present.

Past literature has stated that if a low inversion is present, pollution will dispense in a linear form from the source and grow sideways with no upward aerial growth (Scorer 2002). The average precipitation amounts on high aerosol days and the difference maps of counts and means between high and low aerosol days, showed this linearly expanding dispersion pattern. However, this area was found to not be significant.

5.4 Future Directions

The conversion of land to urban areas is occurring at a rapid pace. This alteration of human disturbance of the climate system will continue to become more significant in the coming future. Future research needs to confirm urban effects on precipitation as well as determine the exact causes on precipitation patterns. Previous research has posed many questions that need to be addressed regarding the role of aerosols on precipitation in and around urban areas. This thesis provides some possible answers to those questions by finding that higher PM 2.5 concentrations coincided with an enhancement of convective storms. This led to significantly higher precipitation amounts on Mondays in the eastern portion of the metro-Atlanta area and the central portion of the metro area on Thursdays. However, the exact role of aerosols on cloud microphysics is still not understood.

This present study needs to be conducted over a longer period of record to obtain a better understanding of precipitation patterns on days with an MT air mass present as well as to obtain a larger sample size to analyze. In order to validate radar estimated precipitation amounts, an analysis of surface-based rain gauges are needed in order to provide "ground truth" amounts. There is also a need for composite surface and upper-level features in the analysis of high and low aerosol days in order to better comprehend the general meteorological factors that are typically present. A more critical analysis of the meteorology of each of the day week is also needed to observe if aerosol scavenging is occurring on Wednesdays to explain the decrease in PM 2.5 concentrations. The use of CAPE and CIN in this work provided information on the convective potential of high and low aerosol days, and continued use of these indices, along with others, will provide a more detailed synoptic understanding of the atmosphere. A case study analysis is needed on each high and low aerosol day to observe where convection develops and its subsequent movement. This can then be analyzed with the meteorology of each high (low) aerosol day to see if similar patterns exist among other high (low) aerosol days. These case studies can establish accurate causes of precipitation development or inhibition. Also, analysis with several cities can help to understand how surface features at differing locations affect cloud processes over many urban areas.

In order to get a better spatial pattern of aerosol distributions, more EPA measuring stations are needed throughout the entire Atlanta-metro area. Also, an analysis of several different types of pollution needs to be completed to see which are responsible for effecting precipitation patterns and amounts. Moderate Resolution Imaging Spectroradiometer (MODIS) derived aerosol optical depths have been shown to be highly correlated with PM 2.5 concentrations from surface stations (Kittaka et al. 2004). The MODIS can provide a regional analysis of the dispersion of PM 2.5 concentrations from Atlanta and surrounding metropolitan areas. Analysis of aerosol concentrations both west and east of the urban, as well as, analyzing the point sources of pollution (i.e., traffic patterns, location of industries) within the metro area can further help to understand aerosol dispersion and possibly explain daily concentrations. These analyses can then give a better representation of aerosols in atmospheric models.

On a broader scale, investigations on how aerosols regulate the microphysical processes in clouds are needed. Currently, longer periods of record are needed on observing systems that measure anthropogenic aerosols to examine any long-term patterns or changes. While EPA observing systems are in place throughout many urban areas, analysis from satellites of the aerosol column concentration can provide data at a much larger spatial extent. Satellites such as the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO), Aura, and Polarization and Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a Lidar (PARASOL) can provide new insight into the role aerosols and clouds have in climate processes. Other satellite systems such as CloudSat can help in understanding cloud processes and Aqua can provide more detailed information on the Earth's water cycle. These satellites can show how the hydrological cycle responds to the microphysical and radiative effects of aerosols.

The study of aerosols in urban areas demonstrates the impact of human development on environmental processes. This thesis showed how aerosols affected urban precipitation patterns and should provide a better understanding when forecasting and researching summer rainfall. The findings will help in determining new ways to interpret the urban effect on the local atmosphere. While research has yet to fully grasp the exact role aerosols play on the atmosphere, much work is still needed. Integration of pioneering new field research, satellite observations, and modeling will pave the way in the understanding of how these little particles are modifying the environment.

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APPENDIX A

Table A.1. Frequency count of radar scans and percent of total radar scans by hour for each day of the week for days when a MT air mass was present in Atlanta.

Hour		Day							Total
		SUN	MON	TUE	WED	THU	FRI	SAT	
0	Count	172	106	99	107	91	107	98	780
	% within Day	4.5%	4.4%	4.6%	4.8%	4.4%	4.1%	4.9%	4.5%
1	Count	173	106	101	105	93	111	101	790
	% within Day	4.5%	4.4%	4.7%	4.8%	4.5%	4.2%	5.0%	4.6%
2	Count	174	103	95	104	89	103	99	767
	% within Day	4.6%	4.3%	4.4%	4.7%	4.3%	3.9%	4.9%	4.4%
3	Count	162	100	90	94	90	96	95	727
	% within Day	4.3%	4.2%	4.2%	4.3%	4.4%	3.6%	4.7%	4.2%
4	Count	159	100	88	96	99	104	88	734
	% within Day	4.2%	4.2%	4.1%	4.3%	4.8%	3.9%	4.4%	4.3%
5	Count	155	101	87	94	99	109	79	724
	% within Day	4.1%	4.2%	4.1%	4.3%	4.8%	4.1%	3.9%	4.2%
6	Count	144	100	87	92	89	103	75	690
	% within Day	3.8%	4.2%	4.1%	4.2%	4.3%	3.9%	3.7%	4.0%
7	Count	144	98	86	86	80	105	73	672
	% within Day	3.8%	4.1%	4.0%	3.9%	3.9%	4.0%	3.6%	3.9%
8	Count	145	98	90	82	78	105	71	669
	% within Day	3.8%	4.1%	4.2%	3.7%	3.8%	4.0%	3.5%	3.9%
9	Count	144	96	90	84	74	108	69	665
	% within Day	3.8%	4.0%	4.2%	3.8%	3.6%	4.1%	3.4%	3.9%
10	Count	141	95	84	85	70	97	66	638
	% within Day	3.7%	4.0%	3.9%	3.8%	3.4%	3.7%	3.3%	3.7%
11	Count	144	94	85	69	63	95	70	620
	% within Day	3.8%	3.9%	4.0%	3.1%	3.1%	3.6%	3.5%	3.6%
12	Count	147	91	83	70	51	93	68	603
	% within Day	3.9%	3.8%	3.9%	3.2%	2.5%	3.5%	3.4%	3.5%
13	Count	148	90	78	77	60	99	74	626

Table A.1. continued

	% within Day	3.9%	3.8%	3.6%	3.5%	2.9%	3.8%	3.7%	3.6%
14	Count	150	87	74	79	67	102	76	635
	% within Day	3.9%	3.6%	3.4%	3.6%	3.2%	3.9%	3.8%	3.7%
15	Count	152	88	82	81	74	103	76	656
	% within Day	4.0%	3.7%	3.8%	3.7%	3.6%	3.9%	3.8%	3.8%
16	Count	153	91	85	83	85	114	76	687
	% within Day	4.0%	3.8%	4.0%	3.8%	4.1%	4.3%	3.8%	4.0%
17	Count	160	96	84	98	93	122	84	737
	% within Day	4.2%	4.0%	3.9%	4.4%	4.5%	4.6%	4.2%	4.3%
18	Count	163	103	90	101	98	122	90	767
	% within Day	4.3%	4.3%	4.2%	4.6%	4.8%	4.6%	4.5%	4.4%
19	Count	166	108	94	100	97	126	96	787
	% within Day	4.4%	4.5%	4.4%	4.5%	4.7%	4.8%	4.8%	4.6%
20	Count	176	109	97	103	104	123	97	809
	% within Day	4.6%	4.6%	4.5%	4.7%	5.0%	4.7%	4.8%	4.7%
21	Count	178	109	99	106	106	132	96	826
	% within Day	4.7%	4.6%	4.6%	4.8%	5.1%	5.0%	4.8%	4.8%
22	Count	181	108	98	106	107	128	96	824
	% within Day	4.7%	4.5%	4.6%	4.8%	5.2%	4.9%	4.8%	4.8%
23	Count	180	109	99	107	106	131	96	828
	% within Day	4.7%	4.6%	4.6%	4.8%	5.1%	5.0%	4.8%	4.8%
Total	Count	3811	2386	2145	2209	2063	2638	2009	17261
	% within Day	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Table A.2. Same as Table A.1, except for high and low aerosol days.

		Aerosol		Total
Hour		High	Low	High
0	Count	154	110	264
	% within Aerosol	4.6%	4.1%	4.4%
1	Count	154	113	267
	% within Aerosol	4.6%	4.2%	4.4%
2	Count	156	109	265
	% within Aerosol	4.6%	4.0%	4.4%
3	Count	148	103	251
	% within Aerosol	4.4%	3.8%	4.1%
4	Count	145	114	259
	% within Aerosol	4.3%	4.2%	4.3%
5	Count	143	113	256
	% within Aerosol	4.3%	4.2%	4.2%
6	Count	136	114	250
	% within Aerosol	4.1%	4.2%	4.1%
7	Count	131	109	240
	% within Aerosol	3.9%	4.0%	4.0%
8	Count	130	108	238
	% within Aerosol	3.9%	4.0%	3.9%
9	Count	133	107	240
	% within Aerosol	4.0%	4.0%	4.0%
10	Count	122	107	229
	% within Aerosol	3.6%	4.0%	3.8%
11	Count	114	106	220
	% within Aerosol	3.4%	3.9%	3.6%
12	Count	112	104	216
	% within Aerosol	3.3%	3.9%	3.6%
13	Count	118	108	226
	% within Aerosol	3.5%	4.0%	3.7%
14	Count	127	110	237
	% within Aerosol	3.8%	4.1%	3.9%
15	Count	126	112	238
	% within Aerosol	3.8%	4.2%	3.9%
16	Count	134	110	244
	% within Aerosol	4.0%	4.1%	4.0%
17	Count	147	113	260
	% within Aerosol	4.4%	4.2%	4.3%

Table A.2. continued

18	Count	152	116	268
	% within Aerosol	4.5%	4.3%	4.4%
19	Count	151	115	266
	% within Aerosol	4.5%	4.3%	4.4%
20	Count	153	118	271
	% within Aerosol	4.6%	4.4%	4.5%
21	Count	157	124	281
	% within Aerosol	4.7%	4.6%	4.6%
22	Count	158	124	282
	% within Aerosol	4.7%	4.6%	4.7%
23	Count	157	125	282
	% within Aerosol	4.7%	4.6%	4.7%
Total	Count	3358	2692	6050
	% within Aerosol	100.0%	100.0%	100.0%