AN INVESTIGATION OF METROPOLITAN AREAS AND TORNADO DEVELOPMENT; POSSIBLE LINKAGES BETWEEN URBAN POLLUTION AND TORNADO TOUCHDOWN POINTS

by

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# TABLE OF CONTENTS

LIST OF TABLES ............................................................................................................ viii
LIST OF FIGURES ........................................................................................................... x
ABSTRACT ....................................................................................................................... xv

Chapter

1 INTRODUCTION .............................................................................................................. 1

2 THE STANDARD MODEL ............................................................................................... 9
  2.1 Thunderstorm Ingredients ....................................................................................... 10
    2.1.1 Ingredient 1: Moisture ...................................................................................... 10
    2.1.2 Ingredient 2: Instability ................................................................................... 12
    2.1.3 Ingredient 3: Lift ............................................................................................... 14
  2.2 The Standard Model: Statics ..................................................................................... 15
    2.2.1 Stage 1: Cumulus Phase .................................................................................... 15
    2.2.2 Stage 2: Mature Phase ..................................................................................... 16
    2.2.3 Stage 3: Dissipating Phase ............................................................................... 18
  2.3 The Guiding Hypothesis ............................................................................................ 18

3 SEVERE THUNDERSTORM AND TORNADO DEVELOPMENT ....................... 20
  3.1 Superstorm Cell Development .................................................................................. 20
  3.2 Tornadogenesis ....................................................................................................... 22
  3.3 Tornado Spatial Climatology ................................................................................... 25
    3.3.1 Tornado and Dixie Alley ................................................................................... 27
  3.4 Tornado Temporal Distribution ............................................................................... 30

4 POPULATION GROWTH AND URBANIZATION .............................................. 31
  4.1 Urban Growth Theories ............................................................................................ 32
  4.2 Concentric Model .................................................................................................... 33
  4.3 Sector Model ............................................................................................................ 33
  4.4 Nuclei Model ........................................................................................................... 34
  4.5 Factors Contributing Towards Urban Population Growth ..................................... 34
  4.6 Urban Sprawl Implications ....................................................................................... 37
  4.7 Urban Growth and Expanding City Limits ............................................................... 39
10.2 The analysis of the impact of population on tornado occurrence........ 115
10.3 Further Discussion.................................................................................. 117
10.4 Urbanization as the link between human activities and tornadogenesis 118
10.5 Research Caveats and Data Biases ...................................................... 131

11 SUMMARY AND CONCLUSIONS................................................................. 138

11.1 Future Research ...................................................................................... 142

REFERENCES.................................................................................................. 145

Appendix

A TABLES AND FIGURES.................................................................................. 164
B ACRONYMS .................................................................................................. 207
LIST OF TABLES

Table 1: Peer-reviewed journal articles discussing the influence population growth has on the outward expansion of city limits.......................... 40

Table 2: Peer-reviewed journal articles discussing the effect LULC has on meteorological observation stations in close proximity.................. 44

Table 3: Peer-reviewed journal articles discussing the relationship between land surface characteristics and spatial thermal patterns.................. 55

Table 4: Peer-reviewed literature which document some of the links between urbanized areas and pollution levels........................................ 59

Table 5: Peer-reviewed literature documenting the effect impervious surfaces have on both generating and exacerbating the urban heat island effect. 74

Table 6: Peer-reviewed literature discussing the key findings regarding the effect urban regions have on convective processes.......................... 78

Table 7: Peer-reviewed literature linking localized thunderstorm activity and urban influences on the land-atmosphere dynamics.......................... 82

Table 8: Peer-reviewed literature documenting various environmental factors that contribute to the distribution and frequency of tornadoes.......... 88

Table 9: Pollutants that the EPA monitors on a daily, monthly, and yearly basis, together with their unit of measurement and the EPA monitoring standard for each measured pollutant................................. 98

Table 10: Replacing MSAs which lacked adequate EPA pollution data. Replaced MSAs are crossed out in red. Those in yellow are included in the analysis. This is a small sample of the MSAs used for analysis... 99

Table 11: Shows the inadequate pollution data for the original list of 40 MSAs. Ozone was the only pollutant that every MSA recorded during 2010.. 100

Table 12: A side by side comparison of the original list of 40 MSAs (left) and the list with replaced MSAs (right). .............................................. 101

Table 13: Description of the variables used in the analysis along with descriptive statistics. ................................................................. 110

Table 14: SPSS output for all multiple regression models used with the analysis. ................................................................. 116
Table A.1: The various ways urban land-use changes, urban aerosols, and anthropogenic greenhouse gases affect the climate system (Hidalgo et al., 2008, p. 355).

Table A.2: The basic characteristics of surface and atmospheric urban heat islands (UHIs).

Table A.3: The population change for the entire US, each state, and by each region, including Puerto Rico from 2000 to 2010.

Table A.4: Population by Core Statistical Area (CBSA) for 2000 and 2010.
LIST OF FIGURES

Figure 1: ArcGIS shape file depicting all Continental US tornado touchdown points, 1950-2011 along with population density for the year 2000. .................................................... 104

Figure 2: GIS depiction of tornado reports and tracks for 2010, National Weather Service. During 2010, an EF5 tornado was not recorded within the continental United States......................................................... 105

Figure 3: Tornado touchdown points and tracks within MSAs, GIS Image. National Weather Service 2010................................................................. 107

Figure 4: A GIS image of the map that plots tornado touchdown points and tracks. Data from the National Weather Service, 2010. ................................. 108

Figure 5: Frequency distribution of Population Squared Root Transformed. ...... 112

Figure 6: \(O_3\) concentrations (average annual fourth maximum eight-hour) between 1998 and 2002 for (a) Atlanta, GA; (b) New York, NY; (c) Chicago, IL; (d) Los Angeles, CA; (e) Houston, TX; and (f) Portland, OR. ........................................................................................................ 120

Figure 7: Land cover changes occurring in the South-eastern eco-region between 1973 and 2000. .................................................................................. 122

Figure 8: Tornado density hazards for the 1990s ................................................ 123

Figure 9: A GIS image showing the number of tornadoes within each MSA. The amber color represents the various MSAs as defined by the US Census Bureau. .......................................................................................... 127

Figure 10: A GIS image showing the number of tornadoes overlaying the land characteristics defined by the National Land Cover Database. .......... 129

Figure 11: The National Land Cover Database (NLCD) classification legend. .... 130

Figure A.1: Scale definitions along with the time and horizontal scale characteristics of a variety of atmospheric processes........................................... 164

Figure A.2: Buoyancy of a rising air parcel because of condensation and the release of heat into the environment......................................................... 164

Figure A.3: The three stages of thunderstorm development which include the developing stage, mature stage, and dissipating stage. ......................... 165
Figure A.4: Many of the features associated with a supercell. ......................... 165
Figure A.5: The process of vortex stretching and the “Dynamic Pipe Effect.” ........ 166
Figure A.6: The “Bottom Up” formation of tornadoes. ..................................... 166
Figure A.7: The role shear and tilting play in forming tornadoes. ....................... 167
Figure A.8: The average annual number of tornadoes per state between the years from 1991-2010. ................................................................. 167
Figure A.9: Yearly tornado average per 10,000 square miles. ............................ 168
Figure A.10: Tornado probability of occurrence during May between the years of 1982-2011. ................................................................. 168
Figure A.11: Tornado probability of occurrence during June between the years of 1982–2011. ................................................................. 169
Figure A.12: Tornado probability of occurrence during September between the years of 1982–2011. ................................................................. 169
Figure A.13: Tornado probability of occurrence during November between the years of 1982–2011. ................................................................. 170
Figure A.14: Geographical boundaries of “Tornado Alley.” ............................. 170
Figure A.15: Geographical location of “Dixie Alley” shown using mean number of tornado days. ................................................................. 171
Figure A.16: Time of day for “Tornado Alley” when tornadoes occur. ................. 171
Figure A.17: Time of day in “Dixie Alley” when tornadoes occur. ....................... 172
Figure A.18: Time of day over the entire US when tornadoes occur. ................. 172
Figure A.19: The three different urban land use descriptive models. .................. 173
Figure A.20: A map, showing high-resolution housing density across the entire country in (a) 1980; (b) 1990; (c) 2000; (d) 2010; (e) 2020; and (f) 2030. ................................................................. 176
Figure A.21: A map is showing the proportion of the country that is rural compared to urban in 1980. ................................................................. 177
Figure A.22: A map showing the proportion of the country that is rural compared to urban in 2000 .................................................................................................................. 177

Figure A.23: A map showing the proportion of the country that is rural compared to urban in 2020 .................................................................................................................. 178

Figure A.24: Maps of change in population density, exurban land use, and cropland use in the United States from 1950 until 2000 ................................................................. 179

Figure A.25: NLCD geospatial analysis of the distribution and magnitude of land cover change for the continental United States between 2001 and 2011 .................................................................................................................. 180

Figure A.26: This framework shows how the urban ecosystem (lower right) is a driver of (upward arrows) and responder to (downward and horizontal arrows) environmental change. ................................................................................................. 180

Figure A.27: A histogram showing significant trends in minimum (top) and maximum (bottom) temperature anomalies for before and after stations respective periods of significant LULC change .............................................. 181

Figure A.28: Comparison of the six common pollutants measured by the EPA nationwide from 1990-2010 ................................................................................................................. 182

Figure A.29: The overall distribution of total emission estimates nationwide by source category for specified pollutants in 2010 .............................................................................. 183

Figure A.30: Number of people living in counties with air quality concentrations above the threshold levels of the National Ambient Air Quality Standards in 2010 .............................................................................................................. 183

Figure A.31: Shows the National 8-hour ozone level trend from 2001-2010 .......... 184

Figure A.32: National PM$_{2.5}$ trends between 2010 and 2010 ........................................ 184

Figure A.33: National PM$_{10}$ concentrations between 2001 and 2010 ........................ 185

Figure A.34: National US lead concentrations from 2001 until 2010 ........................ 185

Figure A.35: NO$_{2}$ national concentration levels between the years of 2001 and 2010 ........................................................................................................................................ 186

Figure A.36: National CO trend between 2001 and 2010 ............................................. 186

Figure A.37: SO$_{2}$ national concentrations between the years of 2001 and 2010 .... 187
Figure A.38: Path of pollution particles within the atmosphere........................... 187

Figure A.39: Comparison of US economic growth measures and pollution emissions between the years of 1998-2008.............................. 188

Figure A.40: Near the surface atmospheric CO$_2$ concentrations averaged over a 24-hour period along the transect (rural, suburban, and urban sites) for the 5 years of the study................................................................. 188

Figure A.41: Representation of the physical processes regarding the urban microclimate and air pollution. ................................................................. 189

Figure A.42: Detailed breakdown of the various greenhouse gas emissions by sector per year. ................................................................................................. 189

Figure A.43: Relationship between population and pollution varying by region...... 190

Figure A.44: Estimates of the global radiative forcing (W/m$^2$) that result from changes in key-climate related air particles on a global basis between the pre-industrial era and 2005............................................................. 191

Figure A.45: The panel shows the evolution of deep convection in a pristine environment while the bottom panel shows deep convection in a polluted environment................................................................. 192

Figure A.46: The various research studies pertaining to the effects of aerosols on precipitation and precipitation particle size.................................................. 193

Figure A.47: Decadal trends of the maximum temperature averaged for every US station below an elevation of 500m.................................................. 194

Figure A.48: Decadal trends for minimum temperatures averaged for every U.S. station below the elevation of 500m.................................................. 195

Figure A.49: A figure that shows how average annual temperatures have changed in various parts of the country since the early 20$^{th}$ century (Since 1901 for the contiguous 48 states, and 1925 for Alaska). .............................................. 196

Figure A.50: This figure shows how the surface and atmospheric temperatures vary over different land use areas............................................................. 197

Figure A.51: This figure depicts a highly developed urban area (left) which is characterized by 75-100 percent impervious surfaces, which have less moisture available for evapotranspiration than a natural ground cover, which has less than 10 percent impervious cover (right). ...................... 197

xiii
Figure A.52: Conceptual depiction of the diurnal evolution of the urban heat island during calm and clear conditions......................................................... 198

Figure A.53: The response of the ensemble-mean number of days with severe thunderstorm environments (NDSEV) in the late 21st century during winter (DJF), spring (MAM), summer (JJA), and autumn (SON).......... 199

Figure A.54: The future response of CAPE and wind shear in the late 21st century during the winter (DJF), spring (MAM), summer (JJA), and autumn (SON) using an elevated greenhouse gas emissions scenario............... 200

Figure A.55: A time series of the yearly tornado report (blue solid line), days tornadoes occurred (red solid line), Fujita scale F2-F5 tornado reports (green solid line), and population (black dotted line). ...................... 201

Figure A.56: The US population change from 1950 to 2010. ........................................ 201

Figure A.57: The US Census regions and corresponding states................................. 202

Figure A.58: Population change as a percentage across the US for metropolitan and micropolitan statistical areas from 2000 until 2010. ....................... 204

Figure A.59: Population numeric and percentage changes by county from 2000 until 2010......................................................................................... 205

Figure A.60: Population distribution for each county in the US for 2010............... 206

Figure A.61: County Population density for the US, for 2010................................. 206
ABSTRACT

Tornadoes are some of the most destructive forces in nature, responsible for hundreds of fatalities and billions of dollars in damage. Thunderstorm and tornado development are widely understood, especially the interaction of large-scale atmospheric ingredients responsible for producing the most severe weather. The standard model only accounts for atmospheric processes, while failing to account for ecological factors occurring at the local level. This thesis research investigates the potential impact human ecological processes within metropolitan statistical areas may have on tornado development. Specifically, this research attempts to identify linkages between urban air and heat pollution (i.e., Urban Heat Island Effect) and the occurrence of tornadoes. Using a linear regression analysis, the findings of this research show potential for the number of tornadoes to increase with increases in the size of the population (SQRTPop); if they occurred in tornado alley; with increases in the average temperature between April to September of 2010; and with increases in CO₂ (Log₁₀CO₂). The two interaction terms (AprilSeptO₃ and CO₂MeanTemp) that were included within the regression analysis had negative signs. Given that these interactive multiplicative effects were not included in the initial predictions, future research should clarify what they may mean. Overall, the findings are very suggestive in portraying the importance of anthropogenic effects on the occurrence of tornadoes, as predicted by Aguirre et al. (1993) as well as other researchers.
Chapter 1
INTRODUCTION

During December 1997, World Leaders met in Kyoto, Japan to consider adopting a treaty that would help combat excessive greenhouse gas (GHG) emissions, chiefly carbon dioxide (CO$_2$). This treaty was built on the narrative that increasing the temperature of both the Earth’s surface, and atmosphere, would result in catastrophic and irreversible environmental damage (Soon et al., 1999, p. 439). The hypothesis that GHGs contribute to large scale atmospheric temperature increase, which will lead to flooding, an increase in severe weather, and long term world-wide climatological change would eventually be known as global warming (Soon et al., 1999, p. 441).

Within many scientific journals, both “global warming” and “climate change” are used. “Global warming” refers to the increase in surface temperature, while “climate change” includes global warming, and all other aspects that increasing GHG concentrations will affect. A change in temperature alone is not the most severe effect of a changing climate. Changes in sea level and precipitation patterns are more likely to have a greater human impact than just higher temperatures alone. Scientific research regarding climate change will encompass more than just changes in surface temperature (Dunbar, 2015).

Future increases in carbon dioxide concentrations throughout the 21st century is expected to contribute to adverse short and long-term climate change effects. Some adverse climate change effects include Arctic sea ice retreat, increases in rainfall and flooding events, melting permafrost and glaciers, and changes to hurricane intensity
(Forster et al., 2007). Altering the concentrations of many GHGs within the atmosphere disrupts the natural solar radiation budget between the Earth and Sun. Shortly after the Intergovernmental Panel on Climate Change (IPCC) published the 4th Assessment Report, evidence has been found that atmospheric concentrations of many greenhouse gases such as CO₂, nitrous oxide (N₂O), and methane (CH₄) have been increasing (Cubasch et al., 2013, p. 3).

The latest IPCC Special Report addressing the impacts of a temperature increase of 1.5°C above pre-industrial emission levels concludes with high confidence that, “Human activities are estimated to have caused approximately 1.0°C of global warming above pre-industrial levels, with a likely range of 0.8°C to 1.2°C. Global warming is likely to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate (IPCC, 2018, p. 6).” There is high confidence that extreme temperatures are becoming more frequent in many regions, increases in intensity, frequency, and/or amount of heavy precipitation in several regions are occurring, as are increases in the frequency of droughts in some regions, this last one with medium confidence. Additionally, temperature extremes on land are projected with high confidence to warm more than the global mean surface temperature, with the number of hot days projected to increase across most land regions, with the highest increases across the tropics (IPCC, 2018, p. 8-10).

According to the IPCC, global and regional land use transitions are found in all scenarios limiting global warming to 1.5°C. “Such large transitions pose profound challenges for sustainable management of the various demands on land for human settlements, food, livestock feed, fibre, bioenergy, carbon storage, biodiversity and other ecosystem services (high confidence) (IPCC, 2018, p. 12-16).” With high
confidence, the reports conclude that mitigation options that limit the demand for land
development must include the intensification of sustainable land-use practices, the
restoration of ecosystems, and a transition towards less resource-intensive diets (IPCC,

In an article by Patricia Romero-Lankao (2012), she points out that cities are
critical players in both generating and reducing GHG emissions (p. 7). Cities also
centralize large “at risk” populations regarding the direct effects of climate change.
For many cities, the most apparent increased climate change risk comes in the form of
extreme weather events (Huq et al., 2007, p. 3-4). Currently, it is still not possible to
predict how climate change will affect any specific city or geographical location with
any degree of precision or certainty (Huq et al., 2007, p. 5). However, it is not
improbable to begin speculating interactions that climate change may have on large
cities, especially as large cities are highly susceptible to thunderstorms (Hurlbut and
Cohen, 2014, p. 3).

Cities produce 78 percent of anthropogenic carbon emissions, yet only account
for 3 percent of Earth’s land surface (Bereitschaft and Debbage, 2013, p. 612). Despite
many factors such as topography, climate, and economics affecting air quality,
understanding city expansion will help further demonstrate the negative impact of
GHG emissions at both the local and regional scale (Stone, 2008, p. 688-689).
Numerous emissions-based models have been created to estimate the impact of urban
growth on GHG concentrations and air pollution. Overall, these models have
concluded that an increase in high-density and compact development results in a
reduction of GHG emissions, and other air pollutants such as O$_3$ precursors, and
particulate matter (PM) (Bereitschaft and Debbage, 2013, p. 613).
Presently, there are a limited number of studies linking the direct association of urban form and the concentration of air pollution (Ewing, Pendall, and Chen, 2003, p. 175). Specifically, Stone (2008) observed large U.S. cities experiencing higher levels of sprawl, or more sprawl-like morphologies, experienced significantly higher O\textsubscript{3} precursor emissions, higher O\textsubscript{3} concentrations, and significantly more O\textsubscript{3} exceedances (p. 688-689). There may be a host of physical mechanisms responsible for increasing ozone in the Stone (2008) study, but what is certain is that urbanization induces significant problems for human beings, while simultaneously altering the delicate balance between human ecology and the natural environment (Rizwan, Dennis, and Liu, 2008, p. 120).

It would be unwise to speculate a link between pollution and tornado development based solely on higher pollution levels within urban areas. Various other ingredients such as heat and moisture are needed for thunderstorms and tornadoes to develop. The Urban Heat Island (UHI), a phenomenon associated with urbanization, is one possible link that may help to provide additional ingredients needed for thunderstorm and tornado development. Higher heat content within larger cities is associated with anthropogenic pollution from vehicle usage, power generation, air conditioners, and other heat sources. The net effect is that heat is stored and re-emitted by massive artificially made urban infrastructure. Loss of natural vegetation also results from urbanization, which increases surface roughness and reduces the removal of convective heat (Rizwan, Dennis, and Liu, 2008, p. 120).

The mechanisms that may act to produce severe storms, separate or in conjunction with each other, independent of aerosol effects include: increased surface roughness enhancing convergence over and downwind of urban areas, thermal
perturbations from the urban heat island destabilizing the boundary layer generated by sensible and thermal fluxes, the urban surface acting as a source of moisture, and the diversion of precipitation patterns due to the urban canopy layer. Additionally, a recent study has been able to link the effects of convection and precipitation with urban pollutant particles which simulate cloud condensation nuclei (CCN) (Carrió, Cotton, and Cheng, 2010, p. 167-168).

Urbanization and the resulting change in land use/land cover (LULC) can alter regional weather and climate (Pielke and Niyogi, 2010, p. 67-71). The idea of “Chaos Theory” is essential for understanding weather and atmospheric science (Schoeneberger, 2002). “Chaos Theory” defines how processes within a system act randomly and without repetitiveness, and the emergent qualities that can be observed. To the field of meteorology, “Chaos Theory” describes the air flow around single air molecules or groups of them (air masses), while attempting to portray the impact this chaos (randomness) has on both local and regional weather (Schoeneberger, 2002).

Thunderstorm assumptions can be used in accordance with “thermodynamic theory,” more specifically “air parcel” theory to better understand thunderstorm development. “Air parcel” theory deals with thermodynamic properties such as temperature and dew point. To generate upward motion, there are two ways; thermodynamically or physically. Air parcels sink if the parcel of air is cooler than the surrounding environment and tends to rise if the parcel is warmer than the surrounding environment. These physical features combined with topographic changes, can force the parcel of air either upward or downward (Schoeneberger, 2002).

Within the atmosphere, there are also large amounts of energy existing in the form of temperature and moisture gradients, called latent energy in the atmosphere.
When an air parcel rises into a cooler environment, it releases latent heat energy into the surrounding environment. More energy is released when the temperature gradient is greater between the parcel and the environment. When the air parcel is forced to move lower in elevation, it will warm slightly, increasing the dew point temperature. It will have the ability to absorb additional latent heat energy from the surrounding environment (Schoeneberger, 2002).

Another important aspect to thunderstorm formation is the air parcel gaining motion, either upward or downward. If the temperature gradient is large, then the parcel moves upward, sending the warmer energetic air upward, as the colder denser air sinks downwards. The updraft grows from the air parcel gaining motion as the parcel gives off latent heat energy into the surrounding atmosphere. This latent heat release reduces the temperature and dew point, which causes the moisture in the atmosphere to attach to small CCN and falls as rain when particles grow large enough. When the particles fall, the cool air is dragged to the surface further pushing upward the warmer moister air for the process to repeat itself (Schoeneberger, 2002).

Tornadoes are spawn from a rotating storm called a supercell thunderstorm. For a supercell thunderstorm to form, the ingredients for a regular thunderstorm need to be present. To transition from an ordinary thunderstorm to a supercell thunderstorm, a thunderstorm cell needs winds to change direction with height and increase in speed. This speed and directional wind shear provide the updraft rotation which makes the supercell. As the supercell rotates high in the sky, a tornado forms below it, roughly thirty percent of the time. This tornado forms from the descending air from the supercell creating rotation near the ground (Howard, 2016). Moreover, very recently
there is an emerging understanding that tornadoes begin at the land surface which is then supplemented by the descending air.

The above represents a summary of thunderstorm development and tornado formation. The research put forward in this thesis speculates on the possible link between human induced anthropogenic forcing related to metropolitan areas and the physical mechanisms that occur naturally in thunderstorm and tornado development. It is a suggestive study guided by the hypothesis that increased pollution and heat levels within metropolitan areas are capable of artificially increasing the probability of tornado occurrences. Its purpose is to extend to tornado causation present-day understandings of the link between human activity and a host of environmental effects, such as hurricanes, droughts, and floods, amongst a variety of other hazards.

The first section of this thesis begins with a brief discussion of the Standard Model as it pertains to thunderstorm development, along with the additional atmospheric ingredients associated with spawning tornadoes. This section will review the physical mechanisms that are responsible for thunderstorm and tornado development. Building upon Aguirre et al. (1993), who found that urbanized counties and metropolitan areas had increased odds of tornado occurrences compared to rural counties, section 2 begins to build a narrative around some of the physical and ecological differences between urban areas and rural areas. At the basic level, urban areas are defined as locations with high human population densities and many built environmental features compared to the surrounding environment. Cities or urban areas produce a significant amount of greenhouse gas emissions due to an array of contributing factors created by the interaction between humans and the surrounding environment.
As population increases, the natural landscape begins to transform from its natural state to accommodate city growth and urban sprawl, increasing trapped heat and pollution levels. Since the natural landscape regulates heat, moisture, and pollution extremes better than the urban environment does, section 3 investigates how urban heat and moisture gradients affect the microclimate over a city center, specifically the urban heat island effect. Section 4 draws upon the existing literature to provide an explanation about how the urban heat effect alters the microclimate, while replicating the physical mechanisms responsible for the “parcel theory.” The urban heat effect is responsible for creating the higher temperature and moisture gradients needed to replicate atmospheric instability. The pollution particles act as a CCN surface which collect water droplets and help clouds grow and develop. The final section analyzes existing studies which have attempted to establish causation links between urbanization and severe thunderstorms and how a warmer microclimate might aid.
Chapter 2
THE STANDARD MODEL

Tornadoes or severe weather can strike anywhere at any time within the United States, including Hawaii and Alaska (Pateman and Vankat, 2012). These severe convective thunderstorms have the capability of producing high-impact weather such as deadly lightning strikes, significant damaging hail, destructive high wind speeds, torrential downpours, and tornadoes (Trapp et al., 2007, p. 19719).

In the United States, every year millions of dollars in infrastructure damage and property loss result from these weather-related events, alongside to many fatalities and injuries (Trapp et al., 2007, p. 19719). As discussed elsewhere in this study, the region’s most favorable for tornado prone environments are those areas downstream of the main mountain ranges, specifically, the meridionally aligned mountain ranges in North America (Trapp et al., 2007, p. 19719).

These meteorological phenomena occur across a wide range of space and time-scales, with some temporal and spatial scales being smaller than others, while some are much larger than others (Markowski and Richardson, 2009, p. 5). However, thunderstorms and severe weather occur most frequently at the “meso” scale, which is smaller than a “synoptic” scale but larger than a “micro” level. Tornadoes, on the other hand, are the exception to this pattern since they occur on a “micro” scale (Markowski and Richardson, 2009, p. 5).

Figure A.1 (see appendix) shows the American Meteorological Society’s official definition of “mesoscale,” defined as the 2-2000km length scale, with subcategories referring to the horizontal length scales of 200-2000km, 20-200km, and 2-20km. Some of the meteorological phenomena that occur within the “mesoscale”
horizontal length scale includes: convective thunderstorms; squall lines; frontal systems; precipitation bands in tropical and extratropical cyclones; mountain waves; and sea and land breezes (American Meteorological Society, 2012a).

2.1 Thunderstorm Ingredients

Most, if not all thunderstorms originate from cumulus clouds. Some cumulus clouds develop further while others dissipate. There are certain atmospheric conditions required for thunderstorm development to take place (Schroeder and Buck, 1969). Their development depends on three crucial components: moisture in the atmosphere, instability, and some form of a lifting mechanism (Nisley, 2014).

2.1.1 Ingredient 1: Moisture

Moisture is the first component required for thunderstorm development. As air, closer to the surface is lifted higher into the atmosphere, it experiences a cooling effect. When this happens, the available water vapor condenses and form CCN, where the droplets over time grow larger and form clouds (Nisley, 2014). Clouds, however, will not form in the atmosphere if little moisture is available, despite the other components being present at the same time (Schroeder and Buck, 1969). As the condensation process occurs (see Figure A.2 in appendix), latent heat is released into the surrounding atmosphere, making the rising air slightly warmer and less dense in comparison (Nisley, 2014).

The rising air must lift to the Condensation Level (LCL), or when the parcel's air temperature and dew point temperature are equal (Schroeder and Buck, 1969). For significant growth to occur, the rising parcel must be lifted further to the Level of Free Convection (LFC). The LFC is the altitude in the atmosphere in which the
environmental temperature cools quicker than a saturated parcel of air cooling at the moist adiabatic lapse does. The more moisture available in the atmosphere, the easier it is for a parcel of rising air to reach the LFC (Schroeder and Buck, 1969). As the rising parcel continues to release latent heat and reaches the condensation level, the parcel becomes more buoyant forming the updraft of the developing thunderstorm structure (Nisley, 2014).

The largest difference in thermodynamic properties and the behavior of moist and dry air is the cooling process encountered from the lifting of air particles. It occurs when air containing water vapor rises and cools at the dry adiabatic rate of 9.8°C/km. When the lifted air parcel reaches the environmental dew point temperature, the parcel becomes saturated, and the water droplets begin to condense, forming a cloud within the parcel of air. Furthermore, saturation occurs with the release of latent heat happens within the air parcel (Kushnir, 2000).

Water continues to condense as the parcel continues to rise above the LCL. As condensation releases latent heat, the air parcel will continue to warm, partly offsetting the adiabatic cooling. Once the parcel has reached the LCL, it starts to cool at the moist adiabatic rate of 6.5°C/km. Moist air is more stable than dry air due to the release of latent heat involved in moist convection. Due to latent heat release inside the air parcel, it is easier for the air to become warmer than the environment, thus becoming unstable. (Kushnir, 2000).

The available moisture within the lower levels of the atmosphere helps to increase instability by allowing more latent heat to become available in the lower atmosphere. However, increasing the moisture in the midlevel will decrease instability and buoyancy. This decline in stability and buoyancy is due to the moist air being less
dense than the dry air and less efficient at evaporating precipitation as well as the dry air. The evaporation of precipitation particles at or below the cloud level cools the air within the downdrafts inside a cloud, making the air denser, which in turn, increases its downdraft velocity and instability (Nisley, 2014).

2.1.2 Ingredient 2: Instability

The second principal component of thunderstorm formation is instability. Instability is defined as “the tendency for air parcels to accelerate when they are displaced from their original position, especially the tendency to accelerate upward after being lifted (National Weather Service, n.d.).” For thunderstorm development to occur, the air must be conditionally unstable through a thick layer of the atmosphere (Schroeder and Buck 1969). A "cap" associated with convective instability acts to suppress feeble convection. However, the most severe thunderstorms have the capability of puncturing the “cap,” thereby signifying their explosiveness (Sirvatka, 2014).

When the dry air in the midlevels of the atmosphere is advected or moved horizontally over warm and moist air within the lower troposphere, convective instability occurs. The convectively induced instability released due to the dynamic lifting of the air parcel from the surface to mid-levels of the troposphere produces a moist adiabatic lapse rate of air lifted from the lower-levels, and a dry adiabatic lapse rate from the air lifted in the mid-levels of the troposphere (Haby, 2014).

Over time, an increase in the tropospheric lapse rate transforms tropospheric conditions with very limited surface based convective available potential energy (CAPE), into one with large surface based convective available potential energy. Convective instability usually exists in the atmosphere when the mid-levels of the
troposphere are dry, with high dew points existing in the Planetary Boundary Layer (PBL) (Haby, 2014).

Few other processes exist which help to increase atmospheric instability. The first pertains to warmer temperatures in the lowest 5,000ft of the atmosphere, together with cooler temperatures in the mid to upper levels of the atmosphere, around 10,000-35,000ft. The second source is due to an increase in low-level moisture in the air. An example would be a moist air mass with characteristics favorable of high wet-bulb potential temperatures, which is marginally unstable and convective in nature. This unstable and convective nature allows clouds to form readily in conjunction with afternoon surface heating (Nisley, 2014).

In general, the greater the stability in the atmosphere, the stronger the updraft of a thunderstorm will be. Similarly, having high wind shear in the environment may offset, or, compensate, for the weak instability that might be present. Having high atmospheric wind shear allows for rapid intensification and rotation of a thunderstorm updraft, directing the precipitation away from falling back into the updraft, thus increasing the thunderstorm’s duration. Likewise, surface heating and radiational cooling at night contribute to instability in the atmosphere (Nisley, 2014).

Since land surfaces heat up and cool down faster than water surfaces, convective currents over large water bodies materialize during the day. These are known as sea breezes. These convective currents create convergence zones, destabilization, and thunderstorms over land such as in Florida. These thunderstorms persist until solar insolation decreases significantly enough to dissipate the thermal gradient due to unequal heating of the land and water surfaces. The drop-in insulation dissipates the intensity and duration of the sea breeze (Nisley, 2014).
Oppositely, during nighttime, the land surface loses heat faster than the adjacent water body does, resulting in an offshore current known as a land breeze. The land breeze along with some synoptic features, create a convergence boundary over the water, which at times provide the required lift for the thunderstorms to form at night. Similarly, as the water surface emits longwave radiation back to the atmosphere, a layer of cooler airs resides over the warmer body of the water and creates an unstable environment (Nisley, 2014).

2.1.3 Ingredient 3: Lift

The final ingredient required for thunderstorm development is lifting. The lift can be either synoptic or mesoscale in nature. Mesoscale lift helps the initial phase of thunderstorm development, while synoptic lift creates the favorable environments for thunderstorms (Sirvatka, 2014). For cumulus clouds to form, it is necessary for air near the surface to lift to at least the condensation level, or the level within the atmosphere where saturation occurs. For further development, the air must continually lift to the LFC. At this level, the air parcel temperature is warmer than the environment and becomes positively buoyant (Schroeder and Buck, 1969).

The lifting of surface air aloft is needed to overcome any convection inhibition such as an “environmental cap.” This cap is usually a warmer layer of air, about 10-15km aloft, that forms under a broad upper-level ridge. Under this upper-level ridge, air warms and tends to sink gradually due to atmospheric compression. When a capping inversion is present, lift is required to push developing updrafts through this “cap” to allow further thunderstorm development to occur at night (Nisley, 2014).

There are a few known sources of lift, which include: dry lines and cold fronts; the effects of various terrain; differential heating; and sea/land breezes. When low
clouds in the morning hours are eroded away by the sun’s radiation over an area, differential heating occurs. A small thermal gradient acts as a boundary at sunrise and heats the Earth’s surface. Sea and land breezes are a form of differential heating, located near large water bodies (Nisley, 2014).

2.2 The Standard Model: Statics

Convective thunderstorms first start forming from rising air along with warm, moist and unstable air within the environment. The air is forced upward through a variety of mechanisms including unequal heating at the surface by shortwave incoming solar radiation, the effect of terrain and topography, as well as converging surface winds lifted air along shallow boundaries (Ahrens, 1994).

Figure A.3 (see appendix) shows the three stages of a thunderstorm. They include the cumulus stage followed by the mature stage followed by the dissipating stage (Ahrens, 1994). During the cumulus stage, an initial plume of warm, moist air rises, with an updraft velocity increasing with height (Sirvatka, 2014). The rising parcel of air cools and forms the base of the cloud (Schroeder and Buck, 1969). The base of a cloud or LCL is the vertical height within the atmosphere where the relative humidity is 100%. Saturation happens when a parcel rises and cools dry-adiabatically so that the parcel temperature is the same as the dew-point temperature (American Meteorological Society, 2012b).

2.2.1 Stage 1: Cumulus Phase

The condensation formed may develop a single cumulus cloud or form a cluster of cumulus clouds. The lift associated with the rising air parcel can either originate near the surface or at a higher level (Schroeder and Buck, 1969). The
primary energy source that enables the convective circulation in the lower atmosphere derived from the lower-level convergence of air (Sirvatka, 2014). As the cloud continues to build, water vapor is transformed into a liquid or solid cloud particle with the release of latent heat, keeping the air inside the cloud cooler than the surrounding environment while creating instability (Ahrens, 1994). As air ascends, entrainment may also occur, meaning that surrounding cooler and drier environmental air is pulled into a cloud (Sirvatka, 2014).

During the cumulus phase, cloud droplets form and are carried to heights beyond the freezing level where they remain as a liquid at subfreezing temperatures, but form ice crystals at the highest levels within a cloud. Due to the insufficient size of the ice and rain particles, and the significant updraft velocity, they do not fall, but are suspended while continuing to grow (Schroeder and Buck, 1969). The temperature within the cloud is significantly warmer than the surrounding air as condensation releases latent heat, forcing the rising air higher (Mandia, 2014). The weather at the surface during the cumulus phase is affected very little, resulting in surface pressure falling slightly (Schroeder and Buck, 1969).

### 2.2.2 Stage 2: Mature Phase

The mature phase begins once the appearance of the downdraft becomes present within a cumulus cloud (Ahrens, 1994). The downdraft originates from the ice and rain particles becoming large enough to fall once they overcome the updraft velocity (Schroeder and Buck, 1969). These precipitation particles start falling from the top of a cloud where the coldest air resides. The cold air is dragged down along with the precipitation particles, creating frictional drag, which enhances the downdraft velocity (Mandia, 2014).
Some falling precipitation evaporates just below the cloud base, creating negative buoyancy from the evaporative cooling, further increasing the downdraft velocity (Sirvatka, 2014). Many times, advection of cooler and drier air at the midlevel of the atmosphere along with evaporative cooling, further enhances the downdraft velocity (Mandia, 2014). The gradual transition from an updraft to a downdraft happens when the cloud has its greatest strength early in the mature phase (Schroeder and Buck, 1969). Both the updrafts and downdrafts reach their greatest intensity in the middle of the cloud, creating severe turbulence (Ahrens, 1994).

The downdraft becomes most pronounced towards the bottom of the cloud where the cold air cascades downwards towards the surface (Schroeder and Buck, 1969). When the downdraft reaches the surface, it spreads out in all directions, specifically ahead of an advancing thunderstorm, forming the surface gust front. The gust front acts like a cold front, where it forces warm, moist air upwards ahead of the thunderstorm, initiating a new energy source for another cumulus cloud to form (Mandia, 2014). Due to the outflow of frigid air from the downdraft, the first surge of air towards the surface is cold and heavy, resulting in a sudden temperature drop at the surface along with a sharp rise in air pressure until the dome of cold air moves away (Schroeder and Buck, 1969).

The mature phase is the most intense phase of a thunderstorm (Schroeder and Buck, 1969). The heaviest rain occurs during this stage, with the intensity of the cumulonimbus cloud visibly seen as an “anvil” shaped cloud top. This “anvil” shaped cloud top visibly depicts updraft winds in a cumulonimbus cloud reaching the top of the tropopause (Mandia, 2014). The tropopause acts like a “cap,” separating the unstable air in the troposphere from the stable air in the stratosphere (Sirvatka, 2014).
In some very severe thunderstorms, the updraft velocity might become so intense that has the capability to overshoot the tropopause, creating a cloud that extends into the stratosphere, also known as an “overshooting top (Mandia, 2014).”

2.2.3 Stage 3: Dissipating Phase

The final stage or dissipating stage occurs with the weakening of the updraft due to the gust front moving away from the base of the cloud. The gust front no longer enhances the updraft movement of warm and moist air, resulting in the downdraft becoming the strongest during this period and the updraft becoming very weak or non-existent (Ahrens, 1994). A thunderstorm may enter the dissipating phase due to: moist air no longer being lifted into the parent cloud; the presence of strong upper-level wind shear; too much dry air entering the parent cloud; or from an inordinate increase in friction created from the surface below the parent cloud (Mandia, 2014).

2.3 The Guiding Hypothesis

It attempts to extend the model above of tornado causation in significant ways. First posed by Aguirre et al. (1993), the hypothesis is that, given the presence of the necessary atmospheric conditions, local level air pollution, and human-induced heat facilitates, could act as triggers to artificially initiate thunderstorms that are capable of spawning tornadoes (p. 624). Aguirre et al. (1993) offered partial evidence supporting this hypothesis, but other tests using better indicators of pollution are needed (p. 630-631). This thesis research is motivated by the possible presence of complex system dynamics in which Newtonian reasoning usually employed to understand weather systems, as is the case here, is only partially accurate.
If empirical evidence supports the hypothesis, it will argue for the incorporation of earth-surface processes, including the powerful effects of human intervention in the environment, into the established model just described. For such a finding will create doubts about the full validity of the standard model and will facilitate the acceptance of similar research by other scientists that will eventually clarify the mechanisms that are involved (Aguirre et al., 1993, p. 629-630).
Chapter 3

SEVERE THUNDERSTORM AND TORNADO DEVELOPMENT

3.1 Superstorm Cell Development

Most tornadoes, including the deadliest, are spawned by superstorm cells. Superstorm cells defined as storm cells exhibiting mid-level rotation, usually cyclonically, with the highest vorticity coincident with the updraft core. The rotation within the mid-levels is known as the mesocyclone (Geerts and Linacre, 1998). A tornado defined as a violently rotating column of air that connects the ground and a cumulonimbus cloud. This column may or may not be visible. The column becomes visible when water vapor condenses into a cloud, and as the tornado picks up dust and debris from the ground (Midwestern Regional Climate Center, 2014). The most violent tornadoes are always associated with the rotation of supercells (Schultz et al., 2014, p. 1707-1708).

There are some other atmospheric conditions for thunderstorms that are capable of spawning tornadoes (Midwestern Regional Climate Center, 2014). The three most important ingredients for supercell development include: high convective available potential energy in the form of warm moist air in the PBL and much cooler air aloft; large wind shear (backing/veering) with height; and convective inhibition in the form of a stable layer at the top of the PBL 2km above the ground (Geerts and Linacre, 1998). Additionally, a mechanism to “lift” the air such as a cold front or dryline is required (Midwestern Regional Climate Center, 2014).

In the Central United States where flat terrain exists, continental polar, continental tropical, and maritime tropical air masses meet, creating baroclinic environments that are favorable for extratropical cyclones. These extratropical
cyclones bring together the ingredients for severe convective storms including moisture from the Gulf of Mexico, steep lapse rates from the high and dry terrain present from the Rocky Mountains, and vertical wind shear. The pole-to-equator thermal gradients closely tie these ingredients together. Nevertheless, despite the presence of these gradients on the synoptic scale, there is no guarantee that these ingredients will spawn tornadoes because of being brought together (Schultz et al., 2014, p. 1706).

Atmospheric low-level moisture is an essential ingredient for thunderstorm development. Within the central U.S., moisture from the Gulf of Mexico is transported by a low-level jet stream. Additionally, the polar jet stream retreats northward during spring months, allowing for warm and humid air masses located in the south-central and the central United States. Thunderstorms can form in environments that are unstable. Instability usually results from both moisture and temperature differences between the parcel of rising air and the surrounding atmosphere (Midwestern Regional Climate Center, 2014). An example of an unstable atmosphere is when a parcel of air rises and continues to grow and accelerate on its own throughout the air.

Lastly, lift is needed. At times, convection begins from surface heating to a high enough temperature (Midwestern Regional Climate Center, 2014). When this is not present, air mass boundaries, such as fronts, act as the lifting mechanism (Schultz et al., 2014, p. 1708-1709). All convective storms begin when air parcels with significant amounts of CAPE reach the LFC. Drylines are another lifting mechanism. Dry lines act as a front, separating warm, moist air from hot, dry air. Another lifting mechanism is an outflow boundary; they are at the leading edge of cooler air that has been pulled down to the surface because of a thunderstorm. Finally, the last form of
lifting is a result of converging air masses (Midwestern Regional Climate Center, 2014). Figure A.4 (see appendix) helps to summarize the environmental conditions and some of the main features of a superstorm cell (Colorado State University, 2015).

### 3.2 Tornadogenesis

A thunderstorm requires rotation to spawn a tornado. There are three mechanisms responsible for strong rotation within supercell storms. First, there needs to be a mesocyclone, typically with a diameter between 5km and 20km. This mesocyclone circulation is at least an order of magnitude smaller than the actual tornado. The mesocyclone narrowed near the ground by a strong updraft, known as vortex stretching (Geerts and Linacre, 1998). When the mesocyclone occlusions forms, the rear flanking downdraft catches up to the forward flank downdraft gust front. Thus, the updraft is weaker in the lower levels but remains strong aloft (Colorado State University, 2015).

Low-level vorticity results from the mesocyclone and tornado vortex. This vertical vorticity results from tilting of the environmental vorticity and baroclinically generated vorticity along the forward flank gust front of the storm cell. Tornado-genesis initiates when mesocyclone rotation increases above the cloud base. The increased rotation lowers the pressure within the mesocyclone, which increases the upward Pressure Gradient Force (PGF) at the cloud base. This increase in PGF causes the rapid convergence in the sub-cloud layer (Wicker and Wilhelmson, 1995, p. 2675-2676).

Stretching of the vorticity in the convergent flow helps create the tornado vortex. The decaying of a tornado begins when the vertical PGF decrease, or when they reverse in the cloud-base. This change contributes to weakening the updraft
above the tornado. As the updraft continues to weaken, the low-level flow advects the occlusion downdraft around the tornado, surrounding the vortex with a downdraft and low-level divergence. The tornado dissipates when it is cut off from its source of positive vertical vorticity, leaving a broad low-level circulation behind (Wicker and Wilhelmson, 1995, p. 2675-2676).

Vortex stretching (seen in Figure A.5 within appendix) helps to intensify the circulation by conserving angular momentum (Colorado State University, 2015). If the stretching continues throughout the atmosphere, a narrow funnel may result. This funnel will become visible due to the low core pressure. The process of adiabatic expansion causes cooling, which will induce condensation, while the cloud droplets make the funnel visible (Geerts and Linacre, 1998). Despite vortex stretching occurring in almost all supercells, it is insufficient by itself to create a tornado (Colorado State University, 2015).

The second process regarding tornado formation is known as the “Bottom Up” approach, as seen in Figure A.6 (see appendix) (Colorado State University, 2015). Many of these superstorm cells form in sheared environments, where poleward winds exist near the surface with strong westerly winds aloft (Geerts and Linacre, 1998). Within a thunderstorm updraft, vorticity initially arises from tilting and subsequent stretching of horizontal vorticity, associated with the mean vertical wind shear (Markowski and Richardson, 2009, p. 4-5).

As the air begins to rise in the storm’s updraft, these horizontal vortex tubes are tilted, creating a “spin” component around the vertical axis. Vortex tilting is a result of vertical vorticity and is intensified further through vortex stretching (Geerts and Linacre, 1998). Horizontal vorticity tilting by the updraft alone usually results in a
considerable amount of vertical vorticity after the air has risen to a height $\geq$1km above ground level (AGL) (Markowski and Richardson, 2009, p. 4).

The last process spawning tornadoes come from vorticity being advected into a storm’s updraft, as seen in Figure A.7 (see appendix) (Colorado State University, 2015). A cold pool typically forms under mature storms in response to the evaporation of rain below the cloud base. The enhancement of evaporation is due to mid-level entrainment of air, which has a lower equivalent potential temperature as compared to the surface air. The gust front is a boundary existing between the cold air and the warm, moist inflow of air, and the temperature gradient across the gust front generates horizontal vorticity. The vorticity that is baroclinically generated is advected into the cloud, through the main updraft, by low-level inflow over the gust front. Thus, the vorticity advection spins up the updraft (Geerts and Linacre, 1998).

Updrafts do not acquire net rotation if the environmental horizontal vorticity is purely crosswise. However, updrafts consist of a dipole of equally strong positive and negative vertical vorticity extremes that straddle the updraft, with the positive vorticity extremum being located on the right flank of the updraft when looking at wind shear. The negative vorticity extremum is on the left flank of the updraft. The updrafts acquire net cyclonic rotation when the environmental horizontal vorticity has a streamwise component and acquires anticyclonic rotation when it has an antistream component. The correlation between vertical velocity and vertical vorticity increases when the ratio between the streamwise to crosswise vorticity increases, with all else being equal, such as storm-relative wind strength and growth rate of isentropic surfaces (Markowski and Richardson, 2009, p. 4).
Tornadogenesis requires large vertical vorticity to arise from the ground. If vertical vorticity is pre-existing near the ground, the vorticity stretching from the ground is negligible. If vorticity stretching is negligible, then vertical vorticity must first arise from either the tilting of horizontal vorticity or from advection from aloft towards the surface. Tilting alone is not effective in producing vertical vorticity near the surface because of the rising air away from the surface, resulting in horizontal vorticity tilted into the vertical. If the tilting process involves the downdraft, then vertical vorticity advects toward the surface, produced by tilting, and subsequently stretched to form a tornado (Markowski and Richardson, 2009, p. 4-5).

The generation of many tornadic supercells may not always occur along a front. There are three examples where this holds true. The first is when tornadic storms form along with a dryline, which is a zone of strong moisture contrast and a moderate temperature contrast. The second is when tornadic cells develop commonly because of moist, unstable air flowing gently upslope on the high plains (usually towards the west), in regions aided by the enhancement of orthographic lift. Such severe weather on the upslope side is typically found on the cooler side of a synoptic scale front, not along it. Finally, the third way is when hurricane rain bands spawn tornadoes. These three are the alternate ways a tornado may form without the presence of a strong temperature gradient (Schultz et al., 2014, p. 1707-08).

### 3.3 Tornado Spatial Climatology

Tornadoes are a part of severe convective storms that theoretically can occur anywhere on Earth’s surface. Tornadoes are not geographically bound but are most common in the United States (Midwestern Regional Climate Center, 2014). Recorded and documented tornadoes occur in all 50 states, and in many countries, worldwide,
excluding Antarctica (NCEI, n.d.). The reason the United States and to a lesser extent Canada have the highest likelihood of tornado occurrence is a direct result of flat land masses stretching across the sub-tropics and Arctic (Midwestern Regional Climate Center, 2014).

The middle latitudes, between 30⁰ to 50⁰ North or South, provide the most favorable environments for tornadogenesis to occur. Within these regions of the world cold, polar air converges against warmer, more subtropical air creating convective precipitation amongst these collision boundaries (NCEI, n.d.). The very flat land within these regions does not provide a blocking mechanism for the colliding air masses (Midwestern Regional Climate Center, 2014). Additionally, air within the middle latitudes flows at different speeds and different directions throughout the various levels of the troposphere (NCEI, n.d.). Differential air flow results in the speed and directional shear necessary for a storm cell to initiate rotation.

Figure A.8 (see appendix) shows the complete count of tornadoes in the United States, with an average of over 1,000 recorded each year (NCEI, n.d.). Figure A.9 (see appendix) shows the yearly average of tornadoes per 10,000 square miles (Midwestern Regional Climate Center, 2014). Tornadoes arise most frequently between spring and summer months but are still capable of occurring throughout the entire year (Midwestern Regional Climate Center, 2014). Spring and Summer tornado occurrences coincide with the polar jet migration northward and the transition and collision between seasonal air masses (Midwestern Regional Climate Center, 2014).

As the jet stream gradually migrates northward between winter and spring, the probability of tornado occurrence significantly increases when the warm air starts to flow north. Mid to late May is when the highest probability of tornado occurrence
exists (see Figure A.10 in appendix), as favorable conditions transition from the Gulf to the Central and Southern Plains (NCEI, n.d.). By the middle of June, the higher probabilities transition further north into the Central and High Plains, with the tornado probabilities, slowly diminishing throughout the summer and early fall (see Figures A.11 and A.12 within appendix). As shown in Figure A.13 (see appendix) there is also a secondary peak in mid to late November across the southern states, with the probabilities decreasing again through December and January (NCEI, n.d.).

3.3.1 Tornado and Dixie Alley

In the United States, two regions exhibit a high disproportionate frequency of tornadoes (Midwestern Regional Climate Center, 2014). Florida is considered the first region due to the high frequency of daily thunderstorms, in addition to the several tropical storms and hurricanes that impact the Florida peninsula on a yearly basis (NCEI, n.d.). “Tornado Alley” located in the south-central US is considered the second region (NCEI, n.d.). Typically, this area is said to lie between the Great Plains and the Midwest and is thought to be the location of peak tornado occurrence within the US (Rice, 2011).

However, the term “Tornado Alley” has been coined very loosely, so that different publications have different definitions of this area. Concannon, Brooks, and Doswell III (2000) defined “Tornado Alley” as, “The primary area of the US in which significant tornadoes occur most often, in an L-shaped region from Iowa to Oklahoma to Mississippi, with the highest threat in Oklahoma (p. 214).” Schaefer and Tatom (1999) defined “Tornado Alley” as, “Texas, Oklahoma, Kansas, Nebraska, Iowa, Missouri, Arkansas, Louisiana. This region essentially contains the proverbial ‘tornado alley’ where tornadoes are most prevalent (p. 3-4).”
The term “Tornado Alley” devised by two Air Force severe weather forecasters, Major Ernest J. Fawbush and Captain Robert C. Miller, who issued the first tornado forecast, four years earlier (Midwestern Regional Climate Center, 2014). In a 1952 article, they wrote that: “On Feb 15, 1952, Fawbush and Miller set up a new project called, ‘Tornado Alley,’ in which a concentrated study of severe weather activity made over an area extending from Lubbock, Texas to Eastern Colorado and Nebraska (Gagan, Gerard, and Gordon, 2010, p. 146-47).” This nomenclature occurred in various stages. The first stage of naming Tornado Alley began from Lubbock, Texas to Enid, Oklahoma. The second phase of naming Tornado Alley occurred from Enid, Oklahoma to the Nebraska line (Gagan, Gerard, and Gordon, 2010, p. 146-47)."

Years later, the National Oceanic Atmospheric Administration (NOAA) adopted the definition of “Tornado Alley” to be "The region from Central Texas, northward to northern Iowa, and from Central Kansas and Nebraska east to western Ohio (NCEI, n.d.)" However, discretion still must be advised regarding the boundaries of “Tornado Alley” based on the criteria used, such as frequency, intensity, and events per unit area. For the remainder of this analysis, the geographical boundaries of “Tornado Alley” set forth by NOAA (see Figure A.14 in appendix) will be used (Concannon, Brooks, and Doswell III, 2000; NCEI, n.d.).

There is a second area of higher than normal tornado activity across the southern US known as “Dixie Alley” (Midwestern Regional Climate Center, 2014). The origin of the term “Dixie Alley” came from the former National Severe Storms Forecast Center (NSSFC) Director Allen Pearson, who explained that the term came from his work during the Mississippi Delta Outbreak of 21 February 1971 (Gagan, Gerard, and Gordon, 2010, p. 147). This outbreak event had ten long-track tornadoes
that resulted in 121 deaths and more than 1,500 injuries. “Pearson compared that event with the Arkansas-Tennessee outbreak of 21-22 March 1952, where 28 tornadoes struck, killing over 200 people. Both events were in the south, and Pearson coined the phrase ‘Dixie Alley’ in 1971 (Gagan, Gerard, and Gordon, 2010, p. 147).”

This area extends from eastern Texas eastward through Alabama, as shown in Figure A.15 (see appendix) (NCEI, n.d.). More specifically, “Dixie Alley” includes parts of Arkansas, Tennessee, Mississippi, Louisiana and Alabama (Rice, 2011). “Dixie Alley” has a separate tornado maximum that lasts three months in late fall (October – December), compared to “Tornado Alley” where tornadoes occur from late spring until early autumn (NCEI, n.d.).

In a comparison between Tornado Alley and Dixie Alley, Gagan, Gerard, and Gordon (2010) found that the distributions of tornado monthly and daily occurrence varied between Dixie Tornado Alley (DTA) and the Plains Tornado Alley (PTA). The risk of a significant tornado on the day of peak risk is lower for the former than the latter, with the peak less pronounced for the DTA. The risk for tornadoes in the DTA is more persistent, with a more moderate risk through much of the year, compared to the extreme risk during a more “confined season” as observed in the PTA. When the more sustained risk is added up for the entire year, the DTA has at least as high of a risk for strong/violent tornadoes as the PTA, with greater risk for killer tornadoes than the PTA. Similarly, there is a 50% increased risk of strong tornadoes during the overnight hours in the DTA, with about 1/3rd of its killer tornadoes occurring between the hours of 9 pm and 7 am (p. 154).
3.4 Tornado Temporal Distribution

Tornadoes have the capability of occurring during the day or at night, but there is a peak time of day for maximized tornado frequency (Midwestern Regional Climate Center, 2014). The occurrence of tornadoes is directly related to the strength of a thunderstorm (NCEI, n.d.). Thunderstorms usually are the strongest during the afternoon and early evening hours (Midwestern Regional Climate Center, 2014). Most thunderstorm energy comes from solar heating because of daytime heating and latent heat from the condensation of water vapor (NCEI, n.d.). The time of the day least likely to spawn a tornado is during the early morning hours, around dawn, when temperatures are usually the lowest and radiation deficits are the highest (Midwestern Regional Climate Center, 2014). Tornadoes that occur overnight are the most dangerous, as they do not give much warning to people who are asleep (NCEI, n.d.). Figures A.16 – A.18 (see appendix) show the time of tornado occurrence for Tornado Alley, Dixie Alley and the entire US (NCEI, n.d.).
Chapter 4

POPULATION GROWTH AND URBANIZATION

Since the hypothesis guiding this work consists of urban pollution increasing the probability of tornado occurrences within metropolitan areas, it is necessary to examine the link between urbanization and population. Trends in social demography show that for many people, city life continues to be essential; 80% of the population in developed nations live in urban areas, whereas only 20% of people in developing countries do so. Over time, however, there has been an increase in urbanization worldwide as more economic growth takes place and people move from the countryside towards the cities. Not only are humans becoming more urbanized, but the total number of the major cities has also increased (Botkin and Beveridge, 1997, p. 4-6).

As Aguirre et al. (1993) states, disasters result from the interaction between a "human use system" and a “natural events system” (p. 624). Their study showed that human ecological processes significantly influence the probability of tornado occurrences. Likewise, this present study will provide an appropriate foundation for further investigation into the interaction between the various realms of science and society. Specifically, Quarantelli (1991) found that increasing industrialization and urbanization amplified the complexity of communities and their vulnerabilities towards disasters. Human-induced environmental change has widely become known as the most important factor altering the surface of the earth and a factor increasing the frequency of natural catastrophes, along with aggravating such effects as drought, deforestation, floods, atmospheric contamination, volcanoes, and more recently earthquakes (Aguirre et al., 1993, p. 624).
One significant and understudied topic that has emerged recently pertains to urban sprawl and shifting populations. Urban fringes of major metropolitan areas were found to have experienced the most significant growth rate, while the central city areas remain unchanged, or are declining (Greene and Pick, 2006). Urban growth is a regular occurrence; however, sprawling for these growing populations is a recent phenomenon. It is distinct from traditional urban development as modeled by the concentric circle approach created by the urban ecology scholars at the University of Chicago, sectoral, and other traditional models of urban patterns. One major attribute used to depict urban sprawl is the presence of low-density developments and a wide gap between individualized structures and groups of structures within the landscape. These distinct features establish a significant ecological imprint on the environment. Likewise, the division of various land uses has become a secondary characteristic defining urban sprawl (Hall and Ashley, 2008, p. 210).

4.1 Urban Growth Theories

Urban growth is a reasonable and inevitable fact. Hall and Ashley (2008) note that urban sprawl represents a growth distinct from traditional development (p. 209). Urban sprawl can take on various forms. Many times, urban sprawl involves low-density residential developments, known as “edge cities.” These “edge cities” represent clusters of populations and economic activity at the urban fringe, which facilitate business-related activities. Other times, urban sprawl takes the form of planned communities having a distinct “downtown” area or residing near a lake or park. Equally, urban sprawl may resemble individual houses and clusters of houses popping up across formerly rural landscapes (Nechyba and Walsh, 2004, p. 178-79).
Numerous studies synthesize three different descriptive models including the Concentric Zone Model, the Sector Model, and the Multiple Nuclei Model seen in Figure A.19 (see appendix). These models provide the standard framework for understanding patterns of land use within industrial cities while providing an accurate generalization of dedicated land in and around cities. Nonetheless, these models cannot describe patterns of land use for every metropolitan area individually (Changing Cities, n.d.).

4.2 Concentric Model

The concentric model originated from Earnest Burgess in 1920. It depicts urban land use as a set of economic rings, with each ring denoting a different land use. It modeled 20th century observations made originally in Chicago based on the gradual assimilation of European migrants and their migration outward from the city center. The central business district (CBD) was the most accessible location in the city, with major transportation routes stemming from the core of the city. “The rings were: (1) central business district, (2) zone of transition, (3) zone of independent workers’ homes, (4) zone of better residences and (5) zone of commuters, presumed to be professionals (Changing Cities, n.d.).” This model assumed that inner-city housing consisted of families with low economic status. As cities grew, the CBD expanded outward, as low socio-economic families moved to adjacent neighborhoods, and more affluent residents moved further away from the CBD (Changing Cities, n.d.).

4.3 Sector Model

The sector model was put forth by Homer Hoyt after observing consistent patterns within many US cities while building upon the concentric ring model. This
model recognized the location of lower income households near major railroad lines and major commercial establishments. Hoyt later theorized that cities tended to grow in wedge-shaped patterns or sectors, emanating from the CBD, due to the main transportation routes (urban expressways and interstate highways). In many ways, the sector model epitomized an extension to the concentric model, while accounting for the impact transportation systems had on accessibility (Changing Cities, n.d.).

4.4 Nuclei Model

In 1945, Chauncy Harris and Edward Ullman recognized that many US cities did not fit into traditional concentric and sector models used to understand urban structures. In this model, cities of larger size developed substantial suburban areas, with some suburban areas functioning as small business districts. These little suburban business districts functioned as satellite nodes, or nuclei, in which land use patterns formed around. The central business district still served as the major center of commerce, but with specialized cells of activity developing to fulfill the requirements of certain activities clustered together (Changing Cities, n.d.).

4.5 Factors Contributing Towards Urban Population Growth

What exactly attracts people to move and live in cities, in the first place? One study hypothesized that the primary reason for urban growth is increasing urban populations. Urban population growth results from either a natural increase in population or from individuals migrating towards urbanized areas. Natural population growth is a direct consequence of the birth rate exceeding the death rate. On the other hand, migration of people to urbanized areas, defined as the relocation of a person,
household, or group to a new area outside the community of origin for an extended period, is described as internal migration (Bhatta, 2010).

Internal migrations are often described as the outcome of push and pull factors. According to Tiebout (1956) people “sort,” themselves into local jurisdictions based on factors that “pull” people out of central cities, and factors that “push” people out of central cities (p. 416-420). Any condition perceived by a migrant as being detrimental to their overall well-being or economic security is a “push” factor, while any condition or circumstance that attracts individuals into relocating is considered a “pull” factor. Pull factors usually need to be initiated first, for sustained migrations by push factors out of other locations (Bhatta, 2010).

Higher quality basic individual services reside within cities due to economic competition among firms. Compared to rural areas, cities have more job opportunities that cater to different tastes and skill sets of various people (Bhatta, 2010). Cities can also be desirable for their consumption amenities. The lower transport costs in cities make firms more productive and make life outside of work more enjoyable. For instance, Glaeser and Sacerdote (1999) noted that individuals, who live in denser buildings and bigger cities, are more likely to enjoy conversing with their neighbors along with developing other interpersonal relationships (p. S228-229). A natural explanation the authors found is that crowding makes meeting other single people easier and helps facilitate the operation of the marriage market (Costa and Kahn, 2000, p. 1287-88).

Large urban markets also increase the welfare of consumers due to goods having substantial economies of scale. An example would be sporting teams, opera companies, and comprehensive art museums, all who need large audiences to be
successful. For the consumers to enjoy these amenities on a regular basis, living in a city is a necessity. Evidence was found regarding the impact of scale and specialization within the restaurant industry, where the big cities have restaurants that specialize in a wide range of cuisines. Scale economies mean that specialized retail and amenities must be in places large enough to support a critical mass of customers (Glaeser, Kolko, and Saiz, 2001, p. 32).

Glaeser, Kolko, and Saiz (2001) define cities as a spatial concentration of factors working together at the same time and location. The demand for cities is linked to an underlying desire to reduce costs of transporting goods, people, and ideas as well as maximizing the opportunities for cooperation. Wages are higher in cities compared to wages in rural areas. In cities, individuals and businesses are more productive due to a greater efficiency of transporting goods, services, and people in comparison to the countryside, along with improved access to better technology, access to innovation, and human capital in urban areas than in rural areas (p. 30-32).

Productivity, in turn, creates broad structural changes within cities, further enhancing massive migrations of people towards urban areas. The structural changes are a result of improving economic, new trading partners, and changes in political conditions (Mayer, 1999, p. 4029). Similarly, the spatial concentration of economic actors helps increase productivity; while transfers involving the latest new information are easier throughout high-density areas. Lastly, large urban density areas represent diverse markets for employers, thus allowing workers to change jobs quickly while providing the faster flow of ideas across workers. The effect results from contacts, conversations, and new skill sets allowing employees to perform their jobs at higher levels of efficiency (Glaeser, Kolko, and Saiz, 2001, p. 31).
4.6 Urban Sprawl Implications

Despite the several factors which make city life very appealing to large masses of people, current land availability and infrastructure within cities are not capable of supporting urban migrations indefinitely, often resulting in sprawl. Within many urban areas of developed countries, residents lack enough living space, which encourages development in the countryside. In it, there is more land to be bought compared to the inner city, and property costs are significantly lower for countryside development.

Negative impacts of urban sprawl include increasing traffic, placing a burden on local resources, demolishing open space and diminishing the quality of the local scenery. Population growth and sprawl are responsible for environmental degradation and changes to the physical environment, due to the spatial restructuring of cities (Bhatta, 2010). Kirtland et al. (1994) synthesized mounting evidence of the environmental impacts of urban growth and sprawl. The authors noted that the impact on the environment is often significantly larger than the spatial extents suggest (p. 206).

With larger cities and larger population densities, shorter travel distances and more congestion ensues (Bhatta, 2010). Newman and Kenworthy (1988) found the former effect of traveling shorter distances far outweighs the congestion that results from large densities. Vehicles are not as fuel-efficient in bigger cities and require more energy per capita. However, the energy per capita is still far less in densely populated areas because people travel less. When people decide to move out of these densely-populated areas, they consume more energy due to further distances from the suburbia to the central city. More cars on roads and highways means more congestion, leading to more fuel consumption and pollution (p. 163).
Hoffhine, Hurd, Civco, Prisloe, and Arnold (2003) also found that sprawl brought about an array of socioeconomic issues related to the degradation of urban areas and the lower quality of life in the suburbs. This deterioration leads to a disparity in wealth between the two regions (p. 275). Grimm, Grove, Pickett, and Redman (2000) noted that the uncontrolled sprawl and the increased human presence in residential and industrial settings negatively altered the surrounding ecosystem processes (p. 571). Similarly, urbanization also leads to the reduction of farmland, crops, and open space (Zhang, Shou, and Dickerson, 2009). According to Burchell (2005), in the United States alone by 2025 urban growth is predicted to take over more than 7 million acres of farmland, 7 million acres of environmentally sensitive land, and another 5 million acres of other types of lands, for a total of 19 million acres.

Weng, Liu, and Lu (2007) found a positive correlation between land surface temperature and impervious surfaces. The temperature is higher in sprawled areas. When urban expansion disperses further from the metropolitan’s center, a positive feedback loop further exacerbates the urban heat island effect. More driven miles are due to urban expansion, which in turn leads to greater consumption of fuel, producing more carbon dioxide emissions. Not only does the morphology of urban areas contribute to increased temperatures, but it also increases the greenhouse gases that result from more driving (p. 203).

Stone (2008) identified sprawl as a major contributor to air pollution, for its lifestyle depends on automobiles; sprawl increases the consumption of fossil fuels and the emissions of greenhouse gases (p. 688-89). Poor air quality results from more automobiles adding carbon monoxide, carbon dioxide, ground-level ozone, sulfur dioxide, nitrogen oxides, volatile organic compounds, and other microscopic particles.
in the air (Frumkin, 2002, p. 206). Likewise, a rise in temperature also indirectly affects air pollution due to the increased demand for air conditioning, which in turn increases the greenhouse gases emitted from the required power plants (Frumkin, 2002, p. 207).

4.7 Urban Growth and Expanding City Limits

Kolankiewicz, Beck, and Manetas (n.d.) published a very comprehensive review addressing the current and future trends of urban growth, which directly impact land use change and urban sprawl. They concluded that from 2002 to 2010, more than 8.3 million acres of farmland and natural habitat, were cleared, scraped, filled, paved, and built over, to accommodate the human-made environment. During the early 21st century, the US population has been growing by millions of people, which have been identified to be responsible for sprawling over woodlands, wetlands, fields, and pastures. The study concluded that 70% of those losses took place around the largest Urbanized Areas (UAs).

Theobald (2005) argues that it is critical to better understanding the land use changes beyond the urban fringe, into the area known as “exurban sprawl” given the widespread and extensive land use changes that are occurring outside the urban center. Hall and Ashley (2008) noted that a growing US population is moving from cities towards the suburban fringes, building new communities where there were not any before. These altered and developed environments become visible at the urban fringe when comparing US Census data for urban areas for 1990 and 2010. The spatial extent of urban development has increased around the periphery of cities over the 1990 to 2010 period (p. 209).
Rusk and Kelly (1997) found that population growth was 47 percent between the years of 1960 to 1990, for 213 urbanized areas in the United States. During the same period, the urbanized land area increased by 107 percent. The result was urban sprawl, a spatial spread of growth occurring faster than population growth, with dispersed lower density development near and around cities as seen in Figure A.20 (see appendix) (Theobald, 2005, p. 14-15). Due to people in or about metropolitan areas, the municipal limits are also expanding, seen in Figures A.21 - A.23 (see appendix) (Theobald, 2005, p. 15-18). Table 1 provides additional peer-reviewed journal articles supporting the narrative of population growth influencing the outward expansion of city limits.

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<th>Title</th>
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<th>Purpose</th>
<th>Methodology</th>
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<tr>
<td>Rural Land-Use Trends in the Conterminous United States, 1950-2000.</td>
<td>Brown, Johnson, Loveland, and Theobald, 2005</td>
<td>This study attempted to better understand the magnitude and direction of significant land use trends within the US.</td>
<td>The study uses a variety of data sets about population, agricultural land availability, and urbanized land use, along with using an ecoregion classification schematic to measure dominant spatial and temporal trends.</td>
<td>By 2000 a significant share of the population resided in metropolitan counties. Though continuously nonmetropolitan areas contained 11.6 million (27.3 percent) in 2000 compared to 1950, metropolitan areas gained about 114.2 million people (106 percent) by 2000. The &quot;transitional&quot; counties grew more rapidly than the continuous metropolitan counties (165 vs. 95 percent respectively). The total increase in urban population continued to be within metropolitan counties. Figure A.24 (see appendix) depicts many of these observed trends.</td>
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The article begins with an analysis of urban sprawl changes due to lower transportation costs and self-sorting populations. The report also provides a theoretical approach to understanding the societal costs resulting from sprawl. Additionally, the study discusses potential trade-offs and policy implications of controlling urban sprawl.

During the five years between 2006 to 2011, 98.23% and 1.77% of the continental United States, the study mapped land cover as either being unchanged or changed. Urban impervious surface for the total land extent for the continental United States expanded from 6.04% in 2001 to 6.2% in 2006, to 6.34% in 2011. Figure A.25 (see appendix) portrays a geospatial distribution and the magnitude of land cover change on the continental United States between 2001 to 2011.
The purpose of this article was to construct a new sprawl index, built upon existing work while examining urban morphology changes at the Metropolitan Level from 2000 thru 2010. An investigative analysis was conducted on current sprawl indices to weigh their strengths and weaknesses. The newly created index based on previous work was used to describe recent metropolitan area growth and morphology trends. The study performed a comparative analysis using both old and new indices along with including environmental and housing income to speculate predictive power of new index. The report concluded that the overall correlation between metropolitan area population growth among city blocks with densities greater than 200 persons/m² and changes in the sprawl index from 2000 until 2010 is significant, negative, and moderately high. The sprawl index illustrates that population decrease correlates with more sprawl over time and is the only density-based measure to find a significant relationship with price changes in housing.

Urban air pollution rising with higher density land development is well established. Pollution levels usually increase moving towards the city center, leading to an urban-rural gradient regarding air pollution concentrations (Marsh, Grossa, and Thirriot, 1997, p. 224). Likewise, urban areas also experience heat pollution, resulting from the alteration of the energy balance within Earth’s surface, as artificial surfaces replace natural vegetation (Weng and Yang, 2006, p. 1-3). These altered conditions partition incoming solar radiation into fluxes of sensible and latent heat, which further skews sensible heat flux as evapotranspiration surfaces weaken. Latent heat fluxes are
found near more vegetative surfaces, while sensible heat fluxes are more favorable near impervious surfaces (Oke, 1982, p. 1-3).

The thermal variations within an urban area are related to different land use and land cover classes, surface material characteristics, and air flushing rates (Marsh, Grossa, and Thirriot, 1997, p. 227). Each surface component within the urban landscape exhibits unique radiative, thermal, moisture, and aerodynamic properties, which relates to their surrounding environment (Oke, 1982, p. 3-5). The significant relationship between land use/cover and land surface temperature has recently become a topic of interest within the literature, specifically the urban heat island (Weng and Yang, 2006, p. 4).

4.8 Urban Air Pollution & Land Use Change

Urban populations depend on ecosystems providing productive and assimilative capabilities far beyond city boundaries. The “ecological footprints” of these populations are tens of hundreds of times greater than the areas occupied by a city (Grimm et al., 2008, p. 756). But as the “edge” of the city expands into the surrounding rural landscape, it introduces changes in soil composition, artificially built infrastructure, markets, and informal human settlements, all of which exert pressure on fringe ecosystems. These near-urban environments are the glue that links core cities to extended urbanized regions. Figure A.26 (see appendix) shows the local changes in climate that accompany urbanization (Grimm et al., 2008, p. 758).

In a paper that synthesized the dominant spatial and temporal trends in the latter half of the 20th century, (Brown et al., 2005, p. 1851-1852) concluded that beyond the urban fringe, low-density, exurban development accounted for nearly 15 times more area than higher density urbanized development. Greene (2006) argues
that there is a large body of evidence showing that dependence on vehicle usage, unsustainable growth, increased infrastructure costs to accommodate growth, and land use changes, result in increased pollution.

Much of the existing literature on climatic consequences of land use/land cover (LULC) has primarily focused on urbanization (Hale, Gallo, Owen, and Loveland, 2006). Table 2 lists some additional literature which investigates the effect LULC alterations have on surrounding meteorological observation stations.

Table 2: Peer-reviewed journal articles discussing the effect LULC has on meteorological observation stations in close proximity.

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<tr>
<td>A closer look at United States and global surface temperature change</td>
<td>Hansen et al., 2001</td>
<td>This study documents changes that have been made in the Goddard Institute for Space Studies (GISS) analysis of surface temperature change while using the analysis to understand the United States and global temperature changes better.</td>
<td>A comparison between the United States and global surface air temperature changes over the past century was performed using analysis data from both the GISS and the U.S. Historical Climatology Network (USHCN).</td>
<td>Local human effects (urban warming) were found even in suburban and small-town surface air temperature trends, but the effect was modest in magnitude.</td>
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<tr>
<th>Land use/Land cover change effects on temperature trends at U.S. Climate Normals stations</th>
<th>Hale et al., 2006</th>
<th>This study attempted to identify and associate &quot;Normals&quot; stations with changes in local LULC while documenting any climate trends that potentially resulted.</th>
<th>Trends of minimum, maximum, and average temperatures at 366 U.S. Climate Normals stations were analyzed based on changes in land use change as defined by the U.S. Land Cover Trends Project.</th>
<th>There were few temperature trends before time periods of the greatest LULC change, which was evenly split between warming and cooling trends. In times that followed the most considerable LULC change, 95% of the stations observed, exhibited significant trends in minimum, maximum, or mean temperature seen in Figure A.27 (see appendix).</th>
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<tr>
<td>Temperature Trends of the U.S. Historical Climatology Network Based on Satellite-Designated Land Use/Land Cover</td>
<td>Gallo, Owen, Easterling, and Jamason, 1999</td>
<td>The purpose of the study was to determine temperature trends associated with LULC changes by applying a satellite-based designation of general LULC to more than 1200 USHCNs.</td>
<td>From 1950-1996, data from the Defense Meteorological Satellite Program Operational Linescan System (OLS), identified 1221 Historical Climatology Network weather observation stations as either urban, suburban, or rural.</td>
<td>Despite not being statistically significant, the trends did differ between the LULC classes. However, the general (urban, suburban, or rural) LULC associated with surface observation stations appears to be capable of playing a significant role in influencing trends observed in temperatures.</td>
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<td>Temperature response to future urbanization and climate change</td>
<td>Argüeso, Evans, Fita, and Bormann, 2014</td>
<td>To examine the impacts of future urban expansion on local near-surface temperature for Sydney, Australia using the Intergovernmental Panel on Climate Change Emissions Scenario A2 (IPCC A2).</td>
<td>Using both a land use model and The Weather Research and Forecasting model, the study performed a climate simulation for the present climate (1990-2009) and future climate (2040-2059) of a region at 2-km spatial resolution.</td>
<td>Future urbanization will strongly affect minimum temperature. The results also indicated that the changes were mostly due to the increased heat capacity of urban structures and reduced evaporation within the city environment.</td>
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<td>Urban Form, Air Pollution, and CO₂ Emissions in Large U.S. Metropolitan Areas</td>
<td>Bereitschaft and Debbage, 2013</td>
<td>This exploratory study attempted to address the relationships between air pollution and urban morphology among 86 U.S. metropolitan areas.</td>
<td>The quantification of an urban form using preexisting sprawl indexes and spatial metrics applied to remotely sensed land cover data.</td>
<td>Metropolitan areas that showed higher levels of urban sprawl, or sprawl-like urban morphologies, exhibited higher air pollution emissions and CO₂ concentrations when controlling for population, land area, and climate.</td>
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<tr>
<td>Urban Form and Extreme Heat Events: Are Sprawling Cities More Vulnerable to Climate Change Than Compact Cities?</td>
<td>Stone, Hess, and Frumkin, 2010</td>
<td>After controlling variables such as population, land area, and climate, this report found that metropolitan areas experiencing high levels of sprawl, or sprawl-like urban morphologies, exhibited higher air pollution levels and increased CO₂ concentrations.</td>
<td>A widely-published sprawl index was used to measure urban form in 2000 alongside the average annual rate of change regarding Extreme Heat Events (EHEs) between 1956 and 2005.</td>
<td>The study found that the rate of increase in the annual index of EHEs during the period of 1956-2005 in the most sprawling metropolitan regions was more than double the rate of growth seen in the densest urban areas.</td>
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Summarizing many of the studies above about how urban form impacts meteorological conditions, the literature put forth in the previous table demonstrate the significant relationship between regional land use patterns and air quality within the country’s largest metropolitan areas (Stone, 2008, p. 688). Recent evidence continues to show how decreasing surface evapotranspiration and increasing thermal properties are significant drivers of minimum, maximum, and mean temperature response (Argüeso et al., 2014, p. 2183).

The meteorological literature has numerous accounts of how the local heat island, discussed in a later chapter, modifies weather, specifically by creating clouds (Hosler and Landsberg, 1977, p. 98). Diffenbaugh, Scherer, and Trapp (2013) using an ensemble model of global climate model experiments to probe severe thunderstorm response found a healthy increase in the occurrence of severe thunderstorm environments over the eastern United States. Likewise, the study found that after altering atmospheric conditions, the result showed an increase in the number of days that were supportive of convective hazards, possibly tornadic storms (p. 16361).

In sum, urbanization, land use changes, and climate impacts are increasingly interconnected than ever before. Urban areas play a significant role in influencing the local meteorology or urban micro-climate. This important role can be seen directly by the urban heat island effect, and by measures of the energy exchanges between the urban surface and the atmosphere. The subsequent sections provide additional research linking urban pollution to the urban heat island, to warmer temperatures, and to thunderstorm formation.
Chapter 5

CURRENT POLLUTION AND POLLUTION TRENDS

The hypothesis that urban pollution increases the probability of occurrence of tornadoes requires us to examine the link between urbanization and pollution levels. Since 1990, air quality nationwide has significantly improved for the six common pollutants the Environmental Protection Agency (EPA) monitors shown in Figure A.28 (see appendix). These pollutants include O₃, lead (Pb), nitrogen dioxide (NO₂), carbon monoxide (CO), PM, and sulfur dioxide (SO₂) (Our Nation’s Air, 2012, p.1).

5.1 Current Pollution Estimates

O₃ is a secondary pollutant typically formed in the presence of sunlight and a chemical reaction between volatile organic compounds (VOCs) and N₂O. PM is either emitted or formed from various chemical reactions. They also are a by-product of combustion (burning coal, wood, diesel), industrial processes, agriculture (plowing, field burning), and unpaved roads. Pb is a result of smelters (metal refiners) and other metal industries, the combustion of lead-based gasoline from piston engine aircraft, waste incinerators, and battery manufacturing. NO₂ is a result of fuel combustion (electric utilities, industrial boilers, and vehicles) and wood burning. CO is a result of incomplete fuel combustion (especially from cars). SO₂ is also a result of fuel combustion (especially high-sulfur coal), electric utilities and industrial processes, and natural sources such as volcanoes (Our Nation’s Air, 2012, p. 4).

Figure A.29 (see appendix) shows the overall distribution of total emissions nationwide for 2010 (the year used in the statistical analysis below) for the specific pollutants the EPA monitors. Electric utilities contribute to over 60 percent of SO₂ emissions nationwide while agricultural operations account for 80 percent of national
CH₄ emissions. Almost 50 percent of VOCs emissions nationwide originate from solvent use. Highway vehicles and non-road mobile sources combined to contribute approximately 60 percent of national CO emissions. However, pollutant levels differ across regions of the country and within local areas, depending on the size and type of sources present (Our Nation’s Air, 2012, p. 4).

According to the EPA, the total levels of toxic air emissions have decreased approximately by 42 percent between 1990 and 2005 in the US. However, GHG emissions have increased by 7 percent since 1990, even if global GHG emissions grew at a much faster rate. Regardless of the progress in clean air evident by 2010, there were still roughly 124 million people in the US who lived in counties that exceeded one or more of the national ambient air quality standards (NAAQS) as seen in Figure A.30 (see appendix). High ozone levels and particulate pollution levels are still of great concern in many areas of the country (Our Nation’s Air, 2012, p. 6).

5.1.1 Ozone Trends

Figure A.31 (see appendix) shows the overall trend in national ozone levels. Since March 2008, the EPA made national standards more rigid for ground-level ozone and set 0.075 parts per million (ppm) as the 8-hour ozone standard. The overall trend shows that nationally, average ground-level ozone concentrations were 13 percent lower in 2010 as compared to 2001, with a notable decline in 2002. Ozone levels vary on a local scale, with one site showing an increase even as a nearby site show a decrease. Weather plays a significant role in ozone formation and concentration levels; hot and dry days can lead to higher ozone levels during any point of the year (Our Nation’s Air, 2012, p. 9).
5.1.2 Particle Pollution Trends

The EPA has set national standards for particulate matter, with finer grained particles standards are set to be equal or less than 2.5 micrometers (µm) in aerodynamic diameter, or PM$_{2.5}$. Coarse particles have diameters between 2.5 and 10 micrometers. PM$_{10}$ is an indicator measuring coarse particle standards. The two national air quality standards used for particulate matter PM$_{2.5}$ are an annual standard (15 µg/m$^3$) and a 24–hour standard (35 µg/m$^3$). As seen in Figure A.32 (see appendix) (Our Nation’s Air, 2012, p. 12), the 24-hour and annual PM$_{2.5}$ national concentrations have declined by 24 and 28 percent, respectively, between 2001 and 2010. Weather again plays a significant role in the formation of PM$_{2.5}$ concentrations, with higher sulfates concentrations in the summer months, and lower nitrate levels in the winter months. Figure A.33 (see appendix) shows PM$_{10}$ levels between 2001 and 2010 (Our Nation’s Air, 2012, p. 15).

5.1.3 Lead Trends

Between the years of 2001 and 2010, lead levels decreased by roughly 71 percent, as seen in Figure A.34 (see appendix) (Our Nation’s Air, 2012, p. 16). The EPA calculated average concentrations from 39 sites located near large stationary sources along with 63 sites located near large stationary industrial sources. Average levels near the stationary sources (metals processors, battery manufacturers, and mining operations) are nearly eight times higher, compared to sources not located near large stationary sources (Our Nation’s Air, 2012, p. 16).

5.1.4 CO, NO$_2$, and SO$_2$ Trends

Nationally, annual mean concentrations of NO$_2$ have decreased by 33 percent during the years of 2001 and 2010, as seen in Figure A.35 (see appendix) (Our
Nation’s Air, 2012, p. 17). All the recorded levels were below the national EPA annual standard (53 parts per billion (ppb)) (Our Nation’s Air, 2012, p. 17). Similarly, Figure A.36 (see appendix) shows concentrations of 8-hour CO decreased 52 percent between the years of 2001 and 2010. All the concentrations were below the 8-hour standard (9ppm) and the 1-hour standard (35ppm) as set by the EPA. Finally, Figure A.37 (see appendix) shows that the annual mean concentrations of SO₂ decreased by nearly 50 percent between 2001 and 2010. It is worth noting that the overall reduction in all three of these pollutants directly resulted from implementing the various national emissions control programs (Our Nation’s Air, 2012, p. 17).

5.2 Factors Contributing to Metropolitan Pollution

Cities have become increasingly interconnected, and city officials can no longer ignore the impacts of climate change, let alone prevent any catastrophic climate change by acting alone. Economic growth and urbanization have moved in tandem for the last 100 years as reflected in the centralization of economic activity in these regions. More affluent lifestyle choices which people in developed countries have become accustomed to enjoying have a significantly greater impact on greenhouse gas emissions. As the world urbanizes quickly, under the business-as-usual scenario greenhouse gasses will dramatically increase (Cities and Climate Change, 2010).

Since the Industrial Revolution, cities have negatively impacted the environment (Dodman, 2009, p. 185). Sánchez-Rodríguez et al., (2005) argue that interactions between urbanized areas and global environmental change create “…. a diversity of impacts that can be grouped into two broad categories: those originating in urban areas that have a negative effect on global environmental change, and global environmental changes that have adverse effects on urban areas (p. 8).” One such
negative impact is that most cities within the US and many cities worldwide suffer from serious air-quality issues (Mage et al., 1996, p. 681).

According to United Nations (2007), cities were responsible for 75 percent of global energy consumption and 80 percent of greenhouse gas emissions. City greenhouse gas emissions are due to a variety of factors including converting the rural land into urban areas that support high traffic volumes and dense residential and commercial buildings, all of which significantly impact the local air quality and energy balance (George, Ziska, Bunce, and Quebedeaux, 2007, p. 7654). Furthermore, the Clinton Foundation (2016) states that “…approximately 75 percent of all heat-trapping greenhouse gas emissions to our atmosphere is caused by cities; while they only comprise about 2 percent of land mass.”

5.2.1 Vehicle Usage

Nechyba and Walsh (2004) write that the link between urban sprawl and air pollution has two components including increases in emissions per mile traveled due to traffic congestion and increases in vehicle miles traveled associated to lower density residential development. In the United States, the link between vehicle traffic and air pollution is evident. On-road vehicles account for 37 percent of total nitrogen oxides, which plays a significant role in forming ground-level ozone, particulate matter, haze, and acid rain. On-road vehicles also accounted for 27 percent of VOCs, which react with nitrogen oxides to also form ground-level ozone. 62 percent of emissions of carbon monoxide result from on-road vehicles (p. 188).

Between 1970 and 2001, total vehicle miles traveled increased 151 percent from 1.1 trillion miles to 2.8 trillion miles, while over the same period miles traveled by passenger cars and motorcycles grew by over 75 percent from 920 billion miles to
1.63 trillion miles (Nechyba and Walsh, 2004, p. 188). Mage et al. (1996) concluded that motor traffic is a primary source of air pollution within megacities (defined as a city having a population exceeding 10 million by the year 2000). Likewise, motor vehicles within megacities were also a primary source of four out of six air pollutants—CO, NOx, HC (hydrocarbons), and Pb—while contributing to suspended particulate matter concentrations (p. 684). While there has been a decrease in national annual air pollutant emissions since 1990, the greatest drop in lead emissions is due to the removal of lead use in petroleum products (Our Nation’s Air, 2012, p. 5).

Since 1950 the total number of vehicles around the world has increased ten-fold. As cities expand outward, the need for people to drive cars over greater distances and for longer time periods increases (Mage et al., 1996, p. 684). Emissions of air pollutants from motor traffic depend on different factors such as traffic density, driving habits, and the ratio of automobiles to trucks, as seen in Figure A.38 (see appendix) (Mayer, 1999, p. 4031). Hence, it follows that motor vehicle traffic seems to be the most significant source of air pollution, especially in cities.

Despite more miles driven, a growing US economy, increases in population and increases in the demand for energy, the combined emissions of the six common pollutants dropped by 59 percent on average since 1990, as seen in Figure A.39 (see appendix) (Our Nation’s Air, 2012, p. 5). However, Figure A.39 does not control for the decline in US Gross Domestic Product (GDP) between the years of 2008-2009. Also, there are noticeable reductions in total miles driven and energy consumed from 2007 to 2009, resulting from the 2008 economic recession and nationwide oil price spike. These factors showed an increase in 2010, but the data in the figure only addresses trends before 2010 (Our Nation’s Air, 2012, p. 5).
5.3 Previous Studies Linking Metropolitan Areas with Pollution

The conversion of land along with high volumes of traffic and dense residential and commercial infrastructure contribute to roughly 80 percent of overall atmospheric CO$_2$ emissions within urbanized areas (George et al., 2007, p. 7654). Thus, cities are responsible for contributing the largest proportion of anthropogenic emissions such as CO$_2$ and nitrous oxides (Pataki et al., 2006, p. 2092). Altering the natural landscape into roads and buildings also change the albedo and heat capacity of an area, resulting in urban areas remaining significantly warmer than the surrounding landscape (Oke, 1982, p. 1-4).

The warmer temperatures within city centers, compared to the temperature of less built up natural environments, has been recorded since 1833, is known as the heat island effect (Oke, 1982, p. 1-4). Some of the leading factors contributing to the heat island effect include the high thermal conductivity of buildings and other man-made infrastructure, the low albedo and geometry of urban surfaces, along with very low evapotranspiration rates (Taha, Akbari, and Rosenfeld, 1991, p. 123-25). The direct release of excess heat from building ventilation and from vehicle traffic result in city heating that varies on both a yearly and daily basis (Fan and Sailor, 2005, p. 73-75).

5.3.1 Urban Surface Temperature (Heat Pollution)

Table 3 lists studies over the last few decades have provided a better understanding of spatial thermal patterns and their relationship to surface characteristics.
Table 3: Peer-reviewed journal articles discussing the relationship between land surface characteristics and spatial thermal patterns.

<table>
<thead>
<tr>
<th>Title</th>
<th>Author</th>
<th>Purpose</th>
<th>Methodology</th>
<th>Conclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>A New Perspective on Recent Global Warming: Asymmetric Trends of Daily Maximum and Minimum Temperatures</td>
<td>Karl et al., 1993</td>
<td>To investigate the changes in the mean monthly diurnal temperature range (DTR).</td>
<td>The study used both daily maximum and minimum temperatures from more than 2,000 weather monitoring.</td>
<td>The mean minimum temperature has increased three times that of the average maximum temperature during 1951-1990 (0.84°C vs. 0.28°C). The decrease in the diurnal temperature range is approximately equal to the increase in mean temperature. The decrease in daily temperature range is partially related to an increase in cloud cover.</td>
</tr>
<tr>
<td>Heat Island Development in Mexico City</td>
<td>Jauregui, 1997</td>
<td>To describe the climatology of the near surface urban heat island in Mexico City.</td>
<td>Using hourly data from two automatic temperature stations. One station located at a rural site and one station located at an urban site.</td>
<td>The nocturnal heat island was more frequent than the daytime heat island. During February, the maximum intensity of the nocturnal heat island occurred (a dry month with calm, clear nights). Afternoon heat islands had a frequency of 13% and had an intensity of 3-5°C during the wet season. Midday heat islands had an intensity of 4-5°C and occurred 12% of the time during both wet/dry seasons.</td>
</tr>
<tr>
<td>Use of Impervious Surface in Urban Land-Use Classification</td>
<td>Lu and Weng, 2006</td>
<td>To study the feasibility and effectiveness of improving impervious surface mapping. Similarly, based on the combined use of impervious surface and population information, this study also attempted to classify urban land uses.</td>
<td>This analysis extracted impervious surface data from the Landsat Enhanced Thematic Mapper data, based on integrating fraction imagery from linear spectral mixture analysis and land surface temperature data.</td>
<td>The integration of fraction images and surface temperatures could provide improved impervious surface imagery. Five urban land-use classes obtained for Indianapolis, IN with an overall classification accuracy of 83.76%.</td>
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Table 3 continued.

<table>
<thead>
<tr>
<th>Table Title</th>
<th>Author(s)</th>
<th>Details</th>
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</thead>
<tbody>
<tr>
<td>Visualization of urban surface temperatures derived from satellite images</td>
<td>Nichol, 1998</td>
<td>An attempt to represent the temperature of the whole urban surface using a GIS interface, while being able to vary the viewpoint of sun angle and azimuth. Using a model for interpolating 2D thermal satellite data over a 3D urban surface. Since surface and air temperatures closely resembled each other, the model indicated micro-scale climatic variations due to building geometry and surface material changes. These factors were not apparent using a 2D model.</td>
</tr>
<tr>
<td>A remote sensing study of the urban heat island of Houston, Texas</td>
<td>Streutker, 2005</td>
<td>This study attempted to characterize the spatial extent of the urban heat island magnitude without using in-situ measurements while determining if a correlation exists between heat island size and rural temperature. This study used Houston, Texas radiative surface temperature maps derived from satellite sensor data on 27 separate occasions over two years. The rural temperature was inversely correlated to the urban heat island magnitude, while spatial extent was determined to be independent of both heat island magnitude and rural temperature.</td>
</tr>
<tr>
<td>An analysis of urban thermal characteristics and associated land cover in Tampa Bay and Las Vegas using Landsat satellite data</td>
<td>Xian and Crane, 2006</td>
<td>This study attempted an assessment of urban thermal characteristics within the Tampa Bay watershed area (west-central Florida), and the Las Vegas Valley (southern Nevada). The study used remote sensing data from both Landsat 5 and Landsat 7 to quantify the extent of urban land use and development densities. Likewise, sub-pixel impervious surface areas were mapped. The results showed that the Tampa Bay watershed urban area has a daytime heating effect (heat-source), whereas the urban surface of Las Vegas has a daytime cooling effect (heat-sink). The thermal effects strongly correlated to urban development densities, with higher impervious percentages associated with higher surface temperatures.</td>
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Table 3 continued.

<table>
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<tr>
<th>The tale of two climates – Baltimore and Phoenix urban LTER sites</th>
<th>This study presented a similar view of temporal temperature patterns for two cities along with indicating the nature of these two cities' past climate research.</th>
<th>Using two Long-Term Ecological Research (LTER) site information to blend physical and social science investigations, this study attempted to understand urban ecological change and evolution better.</th>
<th>This study found that minimum temperatures corresponded to both population and the difference between minimum urban and rural temperatures. As population increases, the difference between minimum urban and rural temperatures also increases. This study also found that the built-up areas within the center of Baltimore had ground level air temperatures that were between 5-10°C warmer than adjacent residential and forested/agricultural areas.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impact of urbanization and land-use change on climate</td>
<td>Kalnay and Cai, 2003</td>
<td>This study used the difference between observed surface temperatures in the continental United States and similar trends from a surface temperature reconstruction using a reanalysis of global weather over the last 50 years.</td>
<td>The study concluded that half of the observed decrease in daily temperature range resulted from urban and other land-use changes. The mean surface temperature was estimated to be 0.27°C warmer per century due to land-use changes, which is twice as high as previous estimates based on urbanization alone.</td>
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57
5.3.2 Air Pollution

Despite improvements, many large-scale cities continue to suffer from serious air-quality concerns, with urban population growth combined with changes in land use identified as major contributors (Mayer, 1999, p. 4029). The urban heat island effect and the elevated use of fossil fuels within major cities are well understood. However, how much of an impact fuel consumption has on elevating atmospheric CO$_2$ concentrations is not well known. Similarly, the climatic effects of yearly variations in elevated atmospheric CO$_2$ concentrations and air temperatures from rural to urban areas seen in Figure A.40 (see appendix) are also not well understood (George et al., 2007, p. 7654).

Within urban areas, human activities also can significantly disturb land-atmosphere carbon dioxide fluxes (Grimmond, King, Cropley, Nowak, and Souch, 2002, p. S243). Equally, urban land-use changes are strongly correlated with increased levels of combustion, fertilization, and sewage release, which in turn significantly increase the amounts of nitrogen compounds into the environment and surrounding climate system (Schlesinger, 2009, p. 203). Nitrous oxide releases generated by humans contribute to atmospheric warming, ozone layer depletion, photochemical smog formation, and acid rain (Seto and Shepherd, 2009, p. 93). Figure A.41 (see appendix) depicts many of the physical interactions within the urban microclimate (Hidalgo, Masson, Baklanov, Pigeon, and Gimeno, 2008, p. 355).

As reported by the Intergovernmental Panel on Climate Change (IPCC), 4th Assessment Report, the overwhelming majority of studies available confirm that anthropogenic influences from greenhouse gas emissions and aerosols were the most significant causes of the current climate trends. The report found that energy consumption and production were the primary sources of greenhouse gas emissions,
alongside industrial activities and transportation-related activities that also made meaningful contributions (IPCC, 2007, p. 3). Also, agricultural related activities and land use changes contributed to roughly 27 percent of total greenhouse gas emissions (IPCC, 2007, p. 3). The GHG emission breakdown is in Figure A.42 (see appendix).

The National Aeronautics Space Administration (NASA) did a study that related the number of people in urban areas to air pollution and found a correlation between large population sizes and greater air pollution (Hansen, 2013). The study focused on nitrogen dioxide and revealed that the combustion of fossil fuels and an increase in tropospheric ozone was a major problem in many urban areas. O₃ is a gas that can be a good proxy for urban air quality, varying by each region of the country, as seen in Figure A.43 (see appendix). The contributing air pollution from surface level NO₂ doubled in each zone as city size increased from 1 million to 10 million people (Hansen, 2013). Table 4 documents the effects of air pollution from urbanized areas.

Table 4: Peer-reviewed literature which document some of the links between urbanized areas and pollution levels.

<table>
<thead>
<tr>
<th>Title</th>
<th>Author</th>
<th>Purpose</th>
<th>Methodology</th>
<th>Conclusion</th>
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<tbody>
<tr>
<td>Elevated Atmospheric CO₂ concentration and temperature across an urban rural transect</td>
<td>George et al., 2007</td>
<td>This study investigated the potential of a high population city center having a similar climate to what is predicted 50-100 years from now due to climate change.</td>
<td>A transect established from an urban site within the center of Baltimore (urban) to the outer suburbs of Baltimore (suburban), and out to an organic farm (rural site), Each location had a weather station set up to monitor environmental variables over a five-year period.</td>
<td>Atmospheric CO₂ levels consistently and significantly increased by 66ppm on average from the rural site to the urban site over the five years. Air temperature also coherently and significantly increased at the urban site (14.8°C) compared to the suburban site (13.6°C) and rural site (12.7°C).</td>
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Table 4 continued.

<table>
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<tr>
<th>Seasonal and diurnal variations of near-surface atmospheric CO₂ concentration within a residential sector of the urban CO₂ dome of Phoenix, AZ, USA</th>
<th>Idso S., Idso C., and Balling, 2002</th>
<th>To better understand the CO₂ dome over Phoenix, AZ.</th>
<th>A permanent weather-monitoring station was set up 2m above a grass lawn in the greater Phoenix area (approximately 0.6 km north of the region’s major east-west freeway and 3km east of its main north-south highway in the suburb of Tempe. Measurements of CO₂, air temperature, relative humidity, wind speed, and wind direction were taken at 5-s intervals and averaged over 1-min periods for an entire year. The results showed that CO₂ concentrations in Phoenix, AZ ranged from a daily minimum of 390 ppm to a daily maximum of 491 ppm, with an outlier observed value of 619ppm. This day-to-day and diurnal fluctuation in CO₂ concentrations suggest that a major source of CO₂ comes from vehicle traffic as peak CO₂ levels correlate to high traffic volume during work days, while being significantly reduced during the weekends.</th>
</tr>
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<tr>
<td>Urban heat islands and landscape heterogeneity: linking spatiotemporal variations in surface temperatures to land-cover and socioeconomic patterns</td>
<td>Buyantuyev and Wu, 2010</td>
<td>This study quantified diurnal and seasonal surface temperature variations within Phoenix, AZ using two spatial scales. This study also explored biophysical and socioeconomic factors responsible for temperature changes.</td>
<td>Surface temperature patterns of two day-night pairs of imagery from summer (June) and autumn (October) were derived and analyzed using the Advanced Spaceborne Thermal Emission and Reflection Radiometer. The urban core was warmer than the rest of the area; there were not any consistent trends found across the urbanization gradient. However, temperature patterns revealed intra-urban temperature differences that were as large, or even bigger than, urban-rural differences. There was also a high correlation between daytime temperatures and median family income. At night, the neighborhood socioeconomic status was a less controlling factor of surface temperatures.</td>
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Table 4 continued.

| **The Greenness of Cities:** Carbon Dioxide Emissions and Urban Development | Glaeser and Kahn, 2010 | An attempt to quantify carbon dioxide emissions associated with new construction in various locations across the country. | This study analyzed emissions from driving, public transit, home heating, and household electricity usage. | There is a significant association between regional land use patterns and air quality for the country’s largest metropolitan areas. The spatial attributes of density and connectivity had a statistically strong and significant association with ozone exceedances after controlling for mean ozone season temperature, population size, and precursor emissions. |
| **Urban Sprawl and Air Quality in Large US Cities** | Stone, 2008 | This study addresses two questions. The first is whether metropolitan regions characterized by high levels of sprawl associate more with ozone precursor emissions from vehicles and industry than do smaller more rural areas. The second is whether metropolitan regions characterized by high levels of sprawl experience more annual ozone exceedance days than do compact areas. | This study analyzed ozone exceedances using a published metropolitan sprawl index in conjunction with yearly ozone exceedance days, precursor emissions, and regional climate data over a 13-year period (1990 – 2002). This study occurred within 45 of the 50 largest US metropolitan regions. | The results show that urban form is significantly associated with both ozone precursor emissions and ozone exceedances during the 13-year study period for 45 US metropolitan regions. A positive correlation was found between sprawl and ozone exceedances was true when controlling for average ozone season (May through September) temperature and seasonal emissions of chemical precursors to ozone formation. Cities that experienced the highest sprawl were found to experience over 60% more ozone days than the most compact cities. |
Table 4 continued.

<table>
<thead>
<tr>
<th>Study</th>
<th>Methodology</th>
<th>Results</th>
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<tbody>
<tr>
<td>An intensive two-week study of an urban CO₂ dome in Phoenix, Arizona, USA</td>
<td>Conducted an intensive investigation of Phoenix’s urban CO₂ dome to determine its strength and intensity.</td>
<td>The study measured atmospheric CO₂ concentrations before dawn and the middle of the afternoon at the height of 2 meters above ground. The study also recorded CO₂ measurements along four transects through the metropolitan area of Phoenix, AZ on 14 consecutive days in January 2000. The study identified a strong but variable urban CO₂ dome at the center of the city, exhibiting peak CO₂ concentrations that were 75% greater than the surrounding areas. Mean city-center peak enhancements were lower, averaging 43% on weekdays and 38% on weekends. Over the surrounding residential area, there are no weekdays-weekend differences in boundary-layer CO₂ concentration. Due to enhanced vertical mixing during the day, near-surface CO₂ levels in the afternoon were lower than levels before sunrise.</td>
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The Environmental Protection Agency reports that air pollutants such as ozone and particle pollution can contribute to climate change. Since ozone and particle pollution stays in the atmosphere for only a few days or weeks, reducing these emissions can help start to offset the impact of climate change in the near-term. Ozone is a significant contributor to the warming of the atmosphere (Our Nation’s Air, 2012, p. 23). Ozone has the greatest climate impact when it is within the troposphere. Concentrations of ozone in this part of Earth’s atmosphere, referred to as “global background ozone,” are a function of “worldwide emissions of CH₄, CO, nitrogen oxide (NOₓ), and VOCs; as well as by natural processes like lightning, and transport from the stratosphere (Cooper et al., 2010, p. 344).” There is also evidence that
ground-level ozone over the US is declining, along with proof of the existence of global background ozone levels continuing to rise (Cooper et al., 2010, p. 344).


Rossi, Seskin, Davis, and Petsios (1996) conducted an analysis in Portland, Oregon known as Land Use, Transportation, and Air Quality (LUTRAQ). It emphasized a compact development scenario that promoted transit-oriented development, pedestrian infrastructure improvements, and transportation demand management policies. This study concluded that these three changes reduced daily VMT by 8% compared to the business as usual scenario of highway expansion.

The land use and vehicle travel statistically significant association have implications for emissions from tailpipe exhaust and air quality, although at present there are only a few studies that document this relationship. The study conclude that NOx and CO were reduced by 6 percent and 3 percent, respectively, in some urban development scenarios (Rossi et al., 1996). Additionally, Frank, Stone, and Bachman (2000) found a significant negative relationship between household density, employment density, street connectivity, and tailpipe emissions when measuring CO, NOx, and VOC emissions. Both studies support the hypothesis that lower density development patterns bring about higher vehicle emissions (p. 173).
5.4 Connecting Pollution to Thunderstorm Development

Particle pollution can also have a significant impact on climate, both directly and indirectly. The direct effect comes from the particle’s effect of absorption and scattering of light. Different types of particles have different effects on climate: some have a warming effect (i.e., black carbon); while others cool it (i.e., sulfates and nitrates) (Our Nation’s Air, 2012, p. 23). Particle pollution can also have significant indirect effects on climate, such as changing the reflectivity of clouds and indirectly influencing cloud lifetime and precipitation. The net result for all particles in the atmosphere is cooling, as scattering dominates (Forster et al., 2007, p. 131-32). However, greenhouse gas emissions play a much larger role in climate change that particle pollution dispersion, as seen in Figure A.44 (see appendix); the Earth is facing a continued warming trend due to radiation absorbed by greenhouse gasses (Forster et al., 2007, p. 131-32).

Seto and Shepherd (2009) write that “Human activities associated with urban land-use (e.g. transportation, energy, and industrial processes) are related to ‘urban’ aerosols or pollution and have been related to high greenhouse gas emissions (p. 90).” Urban centers produce significantly higher carbon dioxide concentrations, in comparison to rural and nonurban areas, although per capita, greenhouse gas emissions may be lower for individuals within urban areas (Seto and Shephard, 2009, p. 90-91). Satterthwaite (2008) writes that cities are responsible for generating anywhere between 75-80 percent of all greenhouse gas emissions (p. 539).

Hidalgo et al., (2008) discussed how urban pollutants, especially aerosols, are leading to climate forcing, which directly affects the local and regional scale. Many aerosols emitted to the atmosphere over severely polluted cities have the same effect as GHGs, but with a different feedback mechanism. This feedback mechanism results
in changes in radiation properties. Aerosol particles also actively influence cloud formation processes through indirect feedback mechanisms (p. 364).

Table A.1 (see appendix) includes studies showing the various ways in which urbanization has an impact on weather and climate processes (Hidalgo et al., 2008, p. 355). Aerosols both indirectly and directly affect regional climate, through radiative forcing mechanisms. Types of aerosols include sulfates, nitrates, ammonium, organics, crystal rock particulate matter, sea salt hydrogen ions, and water. Most of the aerosols found within urban areas are in the form of sulfates, which promote a cooling effect. However, aerosols that are carbon-based tend to absorb solar radiation, exhibiting a warming effect (Seto and Shepherd, 2009, p. 91).

Anthropogenic aerosols not only augment the urban heat island effect by absorbing, re-emitting, and scattering incoming solar radiation and outgoing terrestrial radiation, but aerosols also act as condensation nuclei or ‘seeds’ facilitating the occurrence of cloud microphysical processes seen in Figure A.45 (see appendix) (Rosenfeld et al., 2008, p. 1309-10). Aerosols exhibit an indirect effect that further alters the radiation budget, cloud distributions, and precipitation variability. Urban land use changes also are responsible for altering local and regional atmospheric dynamic and stability conditions required to support thermally directed circulations like sea and land breezes (Rosenfeld et al., 2009, p. 1311-12). The destabilization of the urban heat island, changes in urban surface roughness, and pollution can independently or jointly help initiate, modify, or enhance precipitation cloud systems (Hand and Shepherd, 2009, p. 251).

Khain (2009) compiled research from various authors to create a more holistic understanding of aerosol impacts on cloud formation. Figure A.46 (see appendix),
taken from his study, summarizes the classification of the effects of aerosols on precipitation and cloud formation regarding a high freezing level (p. 13). Lynn et al., (2005) found that aerosols help the formation and intensification of secondary clouds and squall lines (p. 59-60). Similarly, Van Den Heever, Carrió, Cotton, DeMott, and Prenni (2006) find a significant role of aerosols within storm splitting and secondary storm development, along with associated surface precipitation. Two mechanisms are responsible for this intensification. They include aerosol particles leading to new latent heat release, and the air convergence in the boundary layer caused by stronger downdrafts in formerly polluted clouds (p. 1752-53).

The results from Lee, Enfield, Liu, Atlas, and Wang (2013) were that environments which favor high CAPE and high wind shear, typically support cumulonimbus and cumulus type clouds. Tying the literature review back to the standard model of thunderstorm development, the only kind of clouds capable of producing severe weather such as lightning, high winds, and tornadoes are cumulonimbus clouds. And for cumulonimbus clouds to form, vigorous updrafts are required, which elevates clouds tops to higher levels in the atmosphere. At these higher levels, temperatures are significantly colder and would favor frozen precipitation rather than liquid precipitation (p. 1626-1627).

Up to now, this literature review has shown the standard model for thunderstorm development and some of the ingredients required for thunderstorm development. The literature review has also discussed some key factors responsible for urbanization along with the consequences of altering the land surface, such as pollution. Increased amounts of pollution particles released into the atmosphere, in combination with urban areas being warmer than surrounding rural areas, may provide
energy in the form of latent heat release. It is plausible to speculate that the probability of thunderstorms and tornadoes increases with favorable conditions in urban centers. The following chapter argues that with more people, more pollution, and more artificial surfaces, there will be a greater amount of heat energy in the surrounding atmosphere, and this additional heat serves as an ingredient for thunderstorm development.
Chapter 6

THE URBAN HEAT ISLAND (UHI) EFFECT

The central hypothesis that urban pollution increases the probability of occurrence of tornadoes in these areas assumes the presence of temperature differentials and urban heat effects, the topic of this next section of the study. As urban areas continue to develop, changes occur in the landscape where buildings, roads, and infrastructure replace open land, forests and other types of vegetation. Surfaces that were once permeable and moist become impermeable and dry, causing these areas to become warmer than their rural surrounding (Heat Island Effect, n.d.).

Emissions of greenhouse gasses and changes in land use such as urbanization and agriculture are the most important anthropogenic influences on climate (Pielke et al., 2002, p. 1705). A study by Kalnay and Cai (2003) took the difference between observed surface temperature trends in the continental US and the corresponding reconstructed temperature trends from a reanalysis of global weather and were able to estimate the effect changes in land use has on surface warming. Figures A.47 and A.48 (see appendix) show the mean trends for the observations and from the NCEP-NCAR 50-year Reanalysis (NNR), along with the difference between these two patterns (p. 529-530).

The maximum temperature trend in Figure A.47 shows a warming trend in the observations from the eastern and western U.S. and a cooling trend in the Midwest. The Midwest had a slightly negative overall average of -0.017°C per decade. Results from the NNR were similar with a decadal average of +0.008°C. The difference between the observed and reanalysis temperature trends is negative for most of the country east of the Rockies. However, in California, there was a strong positive trend,
while in Oregon, and Washington to a lesser extent, there is an average difference of -0.025°C (Kalnay and Cai, 2003, p. 529-30).

Similarly, Figure A.48 shows that the minimum temperature observations for most of the country are a stronger positive trend averaging +0.193°C each decade. In the NNR, increases in minimum temperature were experienced everywhere except in California and the Midwest, with California averaging +0.113°C each decade. For much of the country, there is a positive difference in minimum temperature trends between observed and NNR values. This pattern has been especially evident in California, where the average was 0.080°C per decade, which is 40 percent of the observed trend. The effect of agricultural development, increasing evaporation during the day, and declines in maximum temperatures from irrigation contribute to increasing minimum temperature. Both urbanization and agriculture increase minimum temperature and slightly decrease maximum temperature (Kalnay and Cai, 2003, p. 529-30).

The elevated air temperatures within city centers compared to less built-up areas has been a phenomenon recorded for over 150 years (Oke, 1982, p. 1-2). The urban heat island has many contributing factors including the thermal conductivity properties of buildings and other human-made structures, the low albedo and geometry of city surfaces, and low evapotranspiration (Taha, Akbari, and Rosenfeld, 1991, p. 123). The heat released directly from building ventilation and vehicular traffic contributes directly to the heating of urban centers, which varies annually and diurnally (Fan and Sailor, 2005, p. 73). The degree of heating within a city varies based on geographical location, building layout, and traffic (George et al., 2007, p. 7655).
The term urban heat effect is used here to describe the thermal characteristic of both the environment and surfaces within cities (urban areas) compared to their surroundings (rural areas) (Voogt, 2004). Table A.2 shows the surface and atmospheric characteristics of urban heat islands (U.S. Environmental Protection Agency, 2008). These heat islands occur on hot, sunny summer days where the sun warms dry and exposed artificial surfaces to temperatures 50⁰-90⁰F hotter than the adjacent air while the surrounding shaded and moist rural surfaces remain close to the average environmental air temperature (Heat Island Effect, n.d.). Figure A.49 (see appendix) shows how annual temperate has changed for the United States since the early 20th century (Climate Change and Heat Islands, n.d.).

Surface heat islands are more prominent during the daytime when the sun is shining very intensely but can be present during the evening as well. On the other hand, during the late morning hours and throughout the day, the atmospheric urban heat islands are weak but become stronger after the sunsets because of urban infrastructure slowly releasing heat, as seen in Figure A.50 (see appendix) (Heat Island Effect, n.d.). The yearly average air temperature can be 1.8⁰F – 5.4⁰F warmer than surrounding areas for cities of 1 million or more. During a clear night, the temperature difference can be as high as 22⁰F (Heat Island Effect, n.d.). In 2010, the number of the major cities (population more than 1 million people) was expected to reach about 125. Major cities act as big "ovens" emitting significant amounts of heat, air pollutants, and other waste material (Tang, 2008).

An important cause of the urban heat effect is a result of the gradual replacement of natural surfaces with built surfaces leading to a change in surface albedo properties. These natural surfaces utilize a significant portion of the radiation
absorbed in the evapotranspiration process that releases water vapor, resulting in the air being cooler than the surrounding vicinity. Contrariwise, the built surfaces are composed of a vast number of non-reflective and water-resistant construction materials, causing them to absorb a considerable amount of incident radiation and resulting in the release of heat (Arrau and Peña, 2015).

Vegetation and open land comprise much of the rural landscape. Surface temperatures decrease due to the shade provided by trees and vegetation. Vegetation contributes to reducing air temperature by evapotranspiration, where plants lose water directly into the surrounding air, releasing ambient heat (U.S. Environmental Protection Agency, 2008). Figure A.51 (see appendix) shows how built up areas evaporate less water, which contributes to high surface and air temperatures (U.S. Environmental Protection Agency, 2008). Materials used for construction along with building dimensions and spacing can affect the magnitude of urban heat. Heat island formation favors dense building materials that warm and cool very slowly, the replacement of natural surfaces by impervious ones, which leads to drier urban areas, and the reduction of the evaporation effect, reducing surface reflectivity to solar radiation (Voogt, 2014).

Properties of urban materials such as solar reflectance, thermal emissivity, and heat capacity influence urban heat island development, and they also help determine how the sun’s energy is reflected, emitted, and absorbed. Urban areas consist of artificial surfaces which have lower albedo properties compared to natural surfaces. Built up communities, thus, reflect less and absorb more solar radiation. Surface temperatures increase from absorbed radiation while contributing to the formation of
both surface and atmospheric heat islands (U.S. Environmental Protection Agency, 2008).

Although albedo is a major determinant of a material's surface temperature, thermal emittance also plays a significant role. The ability of a surface to lose heat or emit longwave (infrared) radiation is thermal emittance. Higher emittance value surfaces stay cooler due to the capability of readily releasing heat (U.S. Environmental Protection Agency, 2008). Heat capacity is another important factor contributing to heat island development. Heat capacity refers to a material's ability to store heat. Cities efficiently store the sun's energy as heat within their artificial infrastructure. Large metropolitan areas have the potential to absorb and store roughly twice the amount of solar radiation compared to their rural surroundings during the daytime (U.S. Environmental Protection Agency, 2008).

US cities would require larger amounts electricity for air conditioning and less fuel for heating in a warmer climate (Climate Change and Heat Islands, n.d.). "Research shows that electricity demand for cooling increases 1.5-2.0% for every 1°F (0.6°C) increase in air temperatures, starting from 68-77°F (20 to 25°C), suggesting that 5-10 percent of community-wide demand for electricity is used to compensate for the UHI (Heat Island Effect, n.d.).” In recent decades, current evidence shows that heating demand in the US has decreased in the north and west, while the cooling demand has increased across the southwest (Climate Change and Heat Islands, n.d.).

Climate change has contributed to higher temperatures and longer, more severe and more frequent heat waves. Urban areas already suffering from the urban heat effect bear the brunt of these harsher heat events. Over the last 20 years, the extreme summer heat has become more frequent across the contiguous 48 states (U.S.)
Environmental Protection Agency, 2014) with western regions setting records for some events in 2006 (Melillo, Richmond, and Yohe, 2014, p. 74). Overall demand for electricity, as well as peak demand which usually occurs during the afternoon of hot summer weekdays increases due to climate change (Heat Island Effect, n.d.). Using more power and adding more capacity for its production will result in more emissions of air pollution and the greenhouse gasses that cause climate change (Climate Change and Heat Islands, n.d.).

Current weather conditions, geographical location, time of the day, the season of the year, city form and city functions are all factors that control and alter urban heat islands. The magnitude of the heat island is the most intense under calm and clear weather conditions. Increases in wind speed mix the air more and reduce the strength of the heat island. Furthermore, if there is an increase in clouds, then there is less radiation reaching the surface during the day, which reduces the cooling effect during night time. Similarly, seasonal variations in weather patterns affect the heat islands’ frequency and magnitude (Voogt, 2014). Figure A.52 (see appendix) is a conceptual depiction of the diurnal evolution of the urban heat island during calm and clear conditions (U.S. Environmental Protection Agency, 2008).

Temperature plays a significant role regarding the frequency and magnitude of the urban heat effect. When more people move towards cities, land transitions from rural vegetation to anthropogenic infrastructure and surfaces. These artificial surfaces trap heat for longer periods of time compared to the surrounding areas, causing the urban heat island effect to take shape especially during the night time hours. The urban heat island is responsible for making the metropolitan area warmer. The increased pollutions in the air also help to trap solar radiation near the surface, creating a more
regulated environment. A more temperate environment holds more moisture, thus producing more thunderstorms and potentially severe thunderstorms and tornadoes.

6.1 Urbanization and the UHI

Urban forms not only impact the local air quality but are also capable of affecting local meteorological factors, including the urban heat island effect. Table 5 lists some well-established studies documenting how impervious surfaces both generate and exacerbate the urban heat island effect.

Table 5: Peer-reviewed literature documenting the effect impervious surfaces have on both generating and exacerbating the urban heat island effect.

<table>
<thead>
<tr>
<th>Title</th>
<th>Author</th>
<th>Purpose</th>
<th>Methodology</th>
<th>Conclusion</th>
</tr>
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<tbody>
<tr>
<td>Upstream Urbanization exacerbates urban heat island effects</td>
<td>Zhang, Shou, and Dickerson, 2009</td>
<td>To better understand how the heat wave events may exacerbate a nonlocal dynamical impact that cascades from urbanization occurring upwind.</td>
<td>The study used both an observational and modeling study of an extreme UHI (heat wave) episode in the Baltimore metropolitan region.</td>
<td>The study found that upstream urbanization increased UHI effects and that the meteorological consequences of extra-urban development can cascade down wind.</td>
</tr>
<tr>
<td>Comparison of impervious surface area and normalized difference vegetation index as indicators of surface urban heat island effects in Landsat imagery</td>
<td>Yuan and Bauer, 2007</td>
<td>To investigate relationships between the land surface temperature (LST), percent impervious surface (%ISA), and the normalized difference vegetation index (NDVI).</td>
<td>The study used both Landsat Thematic Mapper ™ and Enhanced Thematic Mapper Plus (ETM+) data to estimate the LST for four seasons using the Twin Cities, Minnesota metropolitan area.</td>
<td>There was a strong linear relationship between LST and percent impervious surface for all four seasons. The relationship between LST and NDVI is less strong and varies by season.</td>
</tr>
</tbody>
</table>
Table 5 continued.

<table>
<thead>
<tr>
<th>Study</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td><strong>Remote Sensing of the urban heat island effect across biomes in the continental USA</strong>&lt;br&gt;Imhoff, Zhang, Wolfe, and Bounoua, 2010</td>
<td>The study attempted to characterize and inter-compare the UHI response across biomes in the continental U.S. The study used a combination of satellite and ecological map data, to generate comparisons between %ISA and land surface temperature across many cities. The ecological context of the cities biome significantly influences the amplitude of summer daytime UHI the largest. For cities built in biomes dominated by broadleaf and mixed forests, the UHI was 8°C higher. Urban areas on a yearly basis were significantly warmer than the non-urban fringe by 2.9°C, except for arid and semi-arid climates. The UHI’s amplitude both increases with city size and is seasonally asymmetric for many cities.</td>
</tr>
<tr>
<td><strong>Trends in Extreme Temperatures in Relation to Urbanization in the Twin Cities, Metropolitan Area, Minnesota</strong>&lt;br&gt;Sen and Yuan, 2009</td>
<td>To examine long-term trends in extreme summer season temperatures across the Twin Cities, Metropolitan Area (TCMA) in association with urbanization. From 1975 to 2002, the study assembled minimum and maximum temperature trends for seven stations located in both rural and urban areas. Results showed a greater rate of increase in overall minimum temperatures, leading to a declining trend in the diurnal temperature range for all the stations. Most of the peripheral urban and rural stations experienced negative trends in extreme maximum temperatures while experiencing positive trends in extreme minimum temperatures.</td>
</tr>
<tr>
<td><strong>Hidden climate change-urban meteorology and the scales of real weather</strong>&lt;br&gt;Janković and Hebbert, 2012</td>
<td>To discuss the scale to which human activities and the urban environment affect the weather. A study was discussion based describing the sequence of discovery of the UHI since the early 19th century along with a discussion of various attempts to apply knowledge of climatic factors to the design and management of settlement. Urban anthropogenic weather modification has begun to be recognized as a significant factor for carbon mitigation as well as for local adaption to global warming’s weather consequences. Without a very detailed understanding of the urban landscape or knowledge of atmospheric hazards and potentials, modeling city weather is impossible.</td>
</tr>
</tbody>
</table>
In many cities marked by the heat island signature, one of the more important aspects of the UHI is its role in initiating and strengthening convection. Lower level winds that pass through rural areas and then through the major cities with irregularly spaced buildings typically experience an increase in turbulent mixing, which creates convection, in response to surface roughness. This turbulent mixing, combined with the effects of the heat island, and convection induced convergence further causes convection (Hjelmfelt, 1982, p. 1239). Similarly, Yang and Li (2014) and Fan, Zhang, Tao, and Mohr (2008) stress the importance of the microphysical effect of aerosols on deep convection and thunderstorm activity. The next section will provide additional literature helping to clarify, albeit speculatively at present, how urbanization, surface roughness, and the urban heat island contribute to spawning severe weather events.
Chapter 7

METROPOLITAN AREAS SPAWNING CONVECTIVE THUNDERSTORMS

As previously stated, LULC has the capability of affecting regional weather and climate on both a regional and microscale (Pielke et al., 2011, p. 828-29). Land surface characteristic heterogeneities such as urban-rural interfaces tend to develop mesoscale boundaries conducive to convective and pre-convective thunderstorm development (Holt et al., 2006, p. 133). Many studies have already documented how urbanization has increased temperature, mesoscale convection, and precipitation amounts, as well as altering local temperatures and heavy rainfall trends (Niyogi et al., 2011, p. 1129). Built up urbanized areas store more heat than the surrounding terrain, which leads to a seasonal diurnal temperature variation gradient and a UHI that can create its mesoscale convergence (Niyogi et al., 2011, p. 1130).

However, the dynamical aspects that relate to convection and precipitation resulting from urbanization are not understood, with the climatology of tornadoes being even harder to quantify (Niyogi et al., 2011, p. 1130). Boruff et al., (2003) found a steady increase in total tornadoes over time, but a major explanation was that more “weaker” tornadoes were reported (p. 103; but see Aguirre et al., 1993). Temporal and spatial reporting errors, the 1990 deployment of the National Weather Service Doppler Radar, variability in collecting severe weather reports for warning verification programs, increased population, greater awareness, and the proliferation of storm chasers and video footage, all influence tornado climatology (Verbout, Brooks, Leslie, and Schultz, 2006, p. 87).
7.1 Urbanization and Convective Processes

The examination of the hypothesis guiding this study that urban pollution increases the probability of tornado and thunderstorm occurrence makes it necessary to examine the frequency of severe weather within these areas, which is the topic of this section. Despite recent literature yielding some insight into connecting global warming with tornado and severe thunderstorm forcings, these relationships remain insufficiently explored due to many significant challenges in observing and numerically modeling tornadoes (Diffenbaugh, Trapp, and Brooks, 2008, p. 553).

Table 6 lists some of the critical findings in the literature about how urban regions affect convection, a crucial ingredient for thunderstorm development.

Table 6: Peer-reviewed literature discussing the key findings regarding the effect urban regions have on convective processes.

<table>
<thead>
<tr>
<th>Title</th>
<th>Author</th>
<th>Purpose</th>
<th>Methodology</th>
<th>Conclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Numerical Simulation of the Effects of St. Louis on mesoscale Boundary-Layer Airflow and Vertical Air Motion: Simulations of Urban vs. Non-Urban Effects</td>
<td>Hjelmfelt, 1982</td>
<td>To examine the relative importance of urban effects, due to the urban heat island and surface roughness, to the effects of local geography on mesoscale boundary-layer convection downwind of St. Louis.</td>
<td>The study used a 3D mesoscale computer model from the University of Virginia.</td>
<td>The study found mesoscale boundary layer upward motion occurred downwind of St. Louis. Also, a comparison with Metropolitan Meteorological Experiment (METROMEX) radar initial echo frequencies suggested that the results of the model were consistent with cloud and precipitation anomalies related to perturbations in boundary-layer dynamics caused by the UHI and surface roughness.</td>
</tr>
</tbody>
</table>
Table 6 continued.

<table>
<thead>
<tr>
<th>Study Title</th>
<th>Authors</th>
<th>Methodology</th>
<th>Results/Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Impact of Land Cover Change on a Simulated Storm Event in the Sydney Basin</td>
<td>Gero and Pitman, 2006</td>
<td>To better understand the overall impact of land cover, change on a simulated storm event.</td>
<td>The study used the Regional Atmospheric Modeling System (RAMS) to run a 1-km grid spacing over the Sydney basin in Australia using NCEP-NCAR reanalysis data. An intense convective storm developed near Sydney’s densely populated business district under current land cover but was absent when using natural land cover conditions. The study also found that the storm was very sensitive to the presence of agricultural land in the southwest of the domain.</td>
</tr>
<tr>
<td>Urban and land surface effects on the 30 July 2003 mesoscale convective system event observed in the southern Great Plains</td>
<td>Niyogi, Holt, Zhong, Pyle, and Basara, 2006</td>
<td>To investigate the urban and vegetation process impact on the prediction of the mesoscale convective system (MCS) observed on 30 July 2003 near Oklahoma City, Oklahoma.</td>
<td>High-resolution simulations were performed using the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS). The baseline for this experiment was the CONTROL simulation, which propagated two storm cells through the Oklahoma City urban region. The NOUCP simulation (used simpler urban surface characteristics) resulted in two cells, with weaker convective intensity. The Canopy Resistance Scheme (GEM) simulation (included photosynthesis) produced one storm cell west of the downtown region, which paralleled to the observed intensity and timing.</td>
</tr>
<tr>
<td>Formation of horizontal convective rolls in urban areas</td>
<td>Miao and Chen, 2008</td>
<td>To investigate the formation of horizontal convective rolls (HCRs) in urban areas.</td>
<td>Using observational and fine-scale numerical simulations. The observed vertical velocity and horizontal wind fields suggest that the time scale for alternating updrafts and downdrafts in the boundary layer is about 30 minutes, and the length of the updraft/downdraft is about 9km. HCRs were also found to be more common in urban boundary layers.</td>
</tr>
</tbody>
</table>
### Table 6 continued.

<table>
<thead>
<tr>
<th>Effects of boundary-layer stability on urban heat island-induced circulation</th>
<th>Baik, Kim, H., Kim, J., and Han, 2007</th>
<th>This study extends upon previous work showing the importance of boundary-layer stability in determining the intensity of urban heat island induced circulation.</th>
<th>A mathematical and theoretical investigation was performed using a nonlinear numerical model (ARPS) and a two-layer linear analytical model.</th>
<th>The numerical study showed that as the boundary layer became less stable, a downwind updraft cell-induced by the urban heat island strengthened. Additionally, the boundary layer became less stable based upon the maximum updraft velocity height and the increasing vertical extent of the updraft cell further downwind. During the daytime, with a nearly neutral or less stable boundary layer, the urban heat island-induced circulation could become strong, even with a weak UHI. This heat island-induced circulation is possibly a mechanism for late afternoon or evening thunderstorm activity.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observations and Numerical Simulations of Urban Heat Island and Sea Breeze Circulations over New York City</td>
<td>Childs and Raman, 2005</td>
<td>This study analyzed observations to numerically simulate the structure of both the mesoscale boundary layer and the microscale boundary layer over New York City.</td>
<td>Observations were made from two Sound Detection and Ranging (SODAR) systems, a 10m micrometeorological tower and five Automated Surface Observing Stations (ASOS) are examined during several synoptic scale flow regimes.</td>
<td>The numerical observations showed the presence of an urban heat island by indicating a night time mixed layer over lower Manhattan. The ARPS model successfully simulated the movement of a sea-breeze frontal boundary through lower Manhattan during the study period, consistent with SODAR observations. Wind field simulations portrayed both a slowing and cyclonic turning of the 10-meter air flow as it moved towards New York City from the ocean.</td>
</tr>
</tbody>
</table>
7.2 Urbanization and Thunderstorm Activity

Thunderstorm activity over time has become susceptible to the effects of local urban heat islands on surface temperature (Karl, Diaz, and Kukla, 1988, p. 1118). Major urban centers can produce sizeable effects on the atmosphere, and under certain situations, these effects have been significant enough to either induce or dissipate thunderstorm activity, while altering rainfall patterns (Bhatia, 2010). Historically, studies that have defined urban-related influences on thunderstorm activity have relied on using a case study approach or a climatological analysis approach using long records in and near the city (Changnon, 2001, p. 162).
Table 7 lists several studies that have documented the impact of local thunderstorm activity resulting from urban influences on the land-atmosphere dynamics.

<table>
<thead>
<tr>
<th>Title</th>
<th>Author</th>
<th>Purpose</th>
<th>Methodology</th>
<th>Conclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assessment of Historical Thunderstorm Data for Urban Effects: The Chicago Case</td>
<td>Changnon, 2001</td>
<td>To address whether urban changes in thunderstorm activity existed over central Chicago.</td>
<td>This study compared storm activity using 40-years of data from 2 urban sites located in Chicago.</td>
<td>The site that was in the city averaged 4.5 more thunderstorm days a year, which was a 12% increase from the adjacent rural site. The results established a sizable and statistically significant increase in storm activity over the central portions of Chicago.</td>
</tr>
<tr>
<td>Simulation of St. Louis, Missouri, Land Use Impacts on Thunderstorms</td>
<td>Rozoff, Cotton, and Adegoke, 2003</td>
<td>To continue previous modeling work of sophisticated boundary conditions accounting for urban geometry employed at the surface.</td>
<td>A storm-revolving version of the RAMS was used over St. Louis, Missouri on 8 June 1999 to simulate the urban atmosphere and deep moist convection.</td>
<td>The enhancement of surface convergence occurred on the leeward side of the city. Sensitivity analysis showed that the UHI played the largest role in initiating deep, moist convection downwind of the site. Convection happens downwind due to the interaction of urban momentum drag and the UHI.</td>
</tr>
<tr>
<td>Summertime Cloud-to-Ground Lightning Activity Around Major Midwestern Urban Areas</td>
<td>Westcott, 1995</td>
<td>To investigate the frequency of cloud-to-ground lightning flashes in three areas: upwind of the city, within the city, and downwind of the city.</td>
<td>In 16 central US cities between 1989-1992, this study used cloud-to-ground lightning flash data collected by the National Lightning Detection Network.</td>
<td>The study found an improvement of lightning frequency between 40-85% for downwind areas. The largest enhancement in lightning activity happened during the afternoon hours when the rural-urban temperature gradient was the smallest, when the atmosphere is usually the most unstable, and when the atmosphere has the most convective ability.</td>
</tr>
</tbody>
</table>
Table 7 continued.

| Enhancement of Cloud-to-Ground Lightning over Houston, Texas | Orville et al., 2001 | To build on an existing study to a small scale of an urban area by increasing the spatial resolution of the analysis from 20km to 5km. | Cloud-to-Ground lightning flash data analyzed between 1989-2000 for an area centered on Houston, Texas. | The elevated flash densities experienced in the summer and winter occurred near the urban areas of Houston. The elevated lightning flashes were a result of several factors including the convergence of air due to the UHI and an increased level of anthropogenic air pollution which produced smaller droplet sizes. |
| Urban heat islands and summertime convective thunderstorms in Atlanta: three case studies | Bornstein and Lin, 2000 | To investigate regional climate and air quality impacts from past, current, and future urbanization of Atlanta, Georgia. | Data from 27 sites in the Atlanta mesonet surface meteorological network were used along with eight National Weather Service sites analyzed between 26 July to 3 August 1996. | An analysis of six precipitation events over the city showed how the convergence zone induced by the UHI was responsible for initiating three of the storms at various times of the day. Moving thunderstorms tend to bifurcate and move around a city due to buildings acting as barriers. |
| Urban modification of thunderstorms: An observational storm climatology and model case study for the Indianapolis urban region | Niyogi et al., 2011 | To understand how urban regions, alter the intensity and composition/structure of approaching thunderstorms due to land surface heterogeneity. | The study used the Indianapolis region to study storm characteristics while comparing storm characteristics of four peripheral rural counties each approximately being 120km away from the urban center. | The study concluded that more than 60% of thunderstorms changed structure over the Indianapolis area compared to only 25% over the rural regions. Additionally, daytime heating and convection were mostly affected, with 71% of storms changing structure compared to only 42% of storms changing at night. |
Table 7 continued.

<table>
<thead>
<tr>
<th>Study</th>
<th>Authors, Year</th>
<th>Methodology</th>
<th>Data Source</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Using GIS to find effects of mesoscale thunderstorm systems with boundary layer formations from January 1950-July 2001</td>
<td>Schoeneberger, 2002</td>
<td>To better understand how the boundary layer or the ground impacts thunderstorm development.</td>
<td>The study used historically known geospatial data from the National Weather Service’s National Climatic Data Center during 1950-2001.</td>
<td>The study showed a relationship with tornado density and intensity to river valleys and hills, given that surface moisture plays a significant role in storm processes.</td>
</tr>
<tr>
<td>Dry and Moist Convection Forced by an Urban Heat Island</td>
<td>Baik, Kim, and Chun, 2001</td>
<td>To extend on a previous study considering a non-hydrostatic, compressible air flow system, and by analyzing precipitation processes to investigate urban heat-island convection and precipitation.</td>
<td>The study used a two-dimensional, non-hydrostatic, and compressible model with explicit cloud microphysical processes.</td>
<td>Results from the moist convection demonstrate that the downwind updraft cell induced by the urban heat island can initiate moist convection, resulting in surface precipitation in the downstream region when basic-state thermodynamic conditions are favorable. As the intensity of the urban heat island increases, the required time for the first cloud water formation decreases and its horizontal location is closer to the heating center.</td>
</tr>
<tr>
<td>Interepochal Changes in Summer Precipitation in the Southeastern United States: Evidence of Possible Urban Effects near Atlanta, Georgia</td>
<td>Diem and Mote, 2005</td>
<td>To explore the possibility of urban effects as a cause for spatial anomalies in precipitation in a zone within 180km of Atlanta, Georgia.</td>
<td>Using daily summer season precipitation data at 30 stations from 1953 until 2002.</td>
<td>The southern stations experienced substantial decreases in precipitation, whereas significant precipitation increases took place at Central/west-central stations. The largest increases occurred at Norcross, Georgia, which is roughly 30km northeast of the downtown metropolitan area. Region wide dew points increased significantly, which is suspected to be caused by urban effects.</td>
</tr>
</tbody>
</table>
Analyzing the Coupled Model Intercomparison Project, Phase 5, global climate model ensemble (CMIP5) Diffenbaugh, Scherer, and Trapp (2013) found links between severe thunderstorm environments and elevated greenhouse gas concentrations. The study found an increase in the occurrence of storm conditions for

| Patterns and Causes of Atlanta’s Urban Heat Island-Initiated Precipitation | Dixon and Mote, 2003 | This study attempted to demonstrate the effect Atlanta’s UHI has on initiating anomalous precipitation regularly, and whether the UHI-initiation precipitation exhibited temporal and spatial patterns. | Using land use maps, radar reflectivity, surface meteorological data, upper-air soundings, and air mass classification types, used to determine where, when, and why precipitation initiates due to Atlanta's UHI. | There were significant spatial and temporal patterns based on 5-year climatological data. The month of July had the greatest number of events, the diurnal peak around midnight. Low-level moisture seemed to be more of a significant factor than the UHI intensity. Under atmospheric conditions that were more unstable than rain-free days, precipitation events tended to occur. However, the atmosphere could not be unstable enough to produce widespread convection. |
| On the impact of urbanization on summertime thunderstorms in Atlanta: Two numerical model case studies | Shem and Shepherd, 2009 | To understand and examine the physical processes linked to the Atlanta “urban rainfall effect” (URE). | Employs the Weather Research and Forecast (WRF) model to simulate convective precipitation for 17 August 2002 (Urban interaction case) and 26th July 1996 (urban initiation case). | A time series of cumulative rainfall totals indicated the same time in both urban and non-urban simulations. Rainfall amounts downwind of the city were 10-13% higher within a strip of 20-50km east of the city for the urban simulations, in comparison to the non-urban simulations, suggesting a modification effect rather than initiation effect. |
the eastern US in response to further global warming, as seen in Figure A.53 (see appendix). Likewise, on days with high CAPE and strong low-level wind shear, the probability of the occurrence of severe thunderstorm environments also increased (p. 16361-62). On the other hand, expected decreases in mean wind shear from global warming can have a negative influence on severe storms. The study found that decreases in wind shear are concentrated in days with low CAPE but had no effect on the total occurrence of severe environments. Furthermore, the study found that shifts towards higher CAPE values occurred during days of minimal convective inhibition, which increases the occurrence of high CAPE/low-convective inhibition days as seen in Figure A.54 (see appendix). Additionally, the projected increase of severe thunderstorm environments is robust across numerous climate models, in response to moderate global warming. The increase in thunderstorm environments suggests robust physical changes that continue to increase greenhouse forcings will increase the occurrence of severe storms (Diffenbaugh, Scherer, and Trapp, 2013, p.16361-63).

From the literature cited above about changes in thunderstorm activity, many factors seem to play a role in altering convective dynamics within cloud formation. Many of the thunderstorm studies above addressed the UHI affecting the microclimate near metropolitan regions. Perhaps due to the conversion of rural surfaces to artificial surfaces, the UHI will increase, resulting in warmer temperatures, more CAPE in the atmosphere, and convection and lift from surface roughness and building barriers. The final section will continue to speculate that metropolitan regions play a role in tornado development.
Chapter 8

METROPOLITAN REGIONS AND TORNADO DEVELOPMENT

Despite the limitations and biases of the tornado reporting system, useful information is still possible (Brooks and Dotzek, 2008, p. 49). Reiterating an earlier point, despite more documented tornadoes, the number tornadoes classified as EF2-EF5 have decreased over the past five decades as seen in Figure A.55 (Diffenbaugh, Trapp, and Brooks, 2008, p. 554). More importantly, caution should be used since this trend can be influenced by “overrating” the severity of tornadoes in the first half of the tornado record (Verbout et al., 2006, p. 93). The increase of F1 tornadoes is real and not the result of more “eyes in the sky.” Aguirre et al. (1993) has shown that there is no significant statistical association between the numbers of F1 tornadoes and the size of county populations throughout the United States. Thus, the discounting of human ecological effects by claiming the presence of spurious relationships to be incorrect.

Cook and Schaefer (2008) state that some of the changes in seasonal tornado activity coincide with the shifting of the jet stream position associated with the El Niño-Southern Oscillation (ENSO). However, there is not a clear consensus regarding the link between tornadoes and natural climate variability (p. 3121). One can speculate that global warming has the potential to affect the frequency, seasonality, and spatial distribution of severe thunderstorms and tornadoes. Severe thunderstorms that do spawn tornadoes result from large scale environments that typically favor large vertical wind shear and CAPE (Brooks, Lee, and Craven, 2003).

Global warming, in general, is expected to increase CAPE within the atmospheric boundary layer due to increased temperature and humidity, while simultaneously weakening vertical wind shear by decreasing the pole-to-equator
temperature gradient (Trapp et al., 2007, p.19722). Regions presently experiencing peak tornado occurrences, may see a reduction of tornadoes due to weaker wind shear. However, a decrease in tornado frequency is possible due to higher CAPE values, which would theoretically increase tornado frequency (Diffenbaugh, Trapp, and Brooks, 2008, p. 554).

As noted, uncertainty exists within the literature regarding the exact effect of a warmer environment for tornado development. Nonetheless, some note-worthy studies in Table 8 address some of the various environmental factors that may contribute to tornado frequency and distribution.

Table 8: Peer-reviewed literature documenting various environmental factors that contribute to the distribution and frequency of tornadoes.

<table>
<thead>
<tr>
<th>Title</th>
<th>Author</th>
<th>Purpose</th>
<th>Methodology</th>
<th>Conclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Will moist convection be stronger in a warmer climate?</td>
<td>Del Genio, Yao, and Jonas, 2007</td>
<td>To explain land-ocean differences in convective updraft speeds using a new version of the GISS general circulation model (GCM).</td>
<td>A comparison analysis was performed using current climatological sea surface temperatures with a proxy climate simulation with double CO₂ concentrations and sea surface temperatures, which were similar to the 2x CO₂ baseline GCM run. The climate sensitivity of the baseline run was 2.7°C.</td>
<td>Changes in the convective intensity in a doubled CO₂ simulation were small because the tropical lapse rates usually follow the moist adiabatic profile. Updrafts strengthened by 1ms⁻¹ with warming in the lightning-producing regions of continental convective storms, due to an upward shift in the freezing level. In the western US, a drier climate reduced the frequency of lightning-producing storms, but the strongest storms occurred 26% more frequently. For the central US, stronger updrafts along with weaker wind shear suggest little change in severe storm occurrence, but the most dangerous storms occurred more often.</td>
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</tbody>
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Table 8 continued.

<table>
<thead>
<tr>
<th>Surface-Based Convective Potential in the Contiguous United States in a Business-As-Usual Future Climate.</th>
<th>Van Klooster and Roebber, 2009</th>
<th>Based upon large-scale variables well resolved by climate model simulations, this study attempted to estimate both the severity and potential for surface-based convective initiation.</th>
<th>This study used a &quot;perfect prong&quot; approach for the contiguous United States using the output from the Parallel Climate Model and the input from the IPCC third assessment A2 scenario.</th>
<th>The study found deep moisture convection to not change relative to interannual variability. However, the potential for severe convection increased on the east side of the Rocky Mountains and across areas in the &quot;Tornado Alley&quot; region of the Midwest U.S. The increase in potential severe convection was attributed to increases in thermodynamic instability.</th>
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<tbody>
<tr>
<td>Observed changes in surface atmospheric energy over land.</td>
<td>Peterson, Willett, and Thorne, 2011</td>
<td>To better understand how the temperature of the surface atmosphere over land has been rising. The study analyzed three components of energy content: Enthalpy, kinetic energy, and latent heat.</td>
<td>The study used long term in-situ data. Humidity data came from the HadCRUH land dataset. Temperature data came from the Global Historical Climatology Network Monthly (GHCN-M) Version 3.</td>
<td>An analysis of all three components depicts a significant increase in global surface atmospheric energy since the 1970s. Kinetic energy has been decreasing but by over two orders of magnitude less than the increases in both enthalpy and latent heat, both of which contribute equally to global increases in heat content.</td>
</tr>
<tr>
<td>Changes in severe thunderstorm environment frequency during the 21st century caused by Anthropogenically enhanced global radiative forcings.</td>
<td>Trapp et al., 2007</td>
<td>This study speculates how the frequency of severe thunderstorms across the United States will behave as a result of enhanced global radiative forcing due to elevated greenhouse gas concentrations.</td>
<td>Using global climate modeling and high-resolution regional climate models to examine environmental and meteorological conditions which foster severe thunderstorms.</td>
<td>Across many of the climate models used, a net increase was observed in the number of days in which severe thunderstorm environmental conditions (NDSEV) occurred during the late 21st century. Many of these increases were attributed to increases in atmospheric water vapor within the PBL, with the largest increases of NDSEV occurring in the warm season, in the Gulf of Mexico and Atlantic coastal regions.</td>
</tr>
<tr>
<td>Transient response of severe thunderstorm forcing to elevated greenhouse gas concentrations.</td>
<td>Trapp, Diffenbaugh, and Gluhovsky, 2009</td>
<td>This study provided a detailed analysis into the transient response of thunderstorm forcing mechanisms to the temporal-varying greenhouse gas concentrations associated with the IPCC A1B emissions scenario.</td>
<td>This study used a five-member global climate ensemble model to run various experiments using different emission scenarios.</td>
<td>The study found a positive trend in the US regarding greenhouse forcings over the period of 1950-2009. The rate of increase varied by geographical region, depending on low-level water vapor availability and transport, and the frequency of synoptic scale cyclones during the warming season. The study also found that a deceleration of the greenhouse gas emissions trajectory would likely lower increases in severe thunderstorm forcing.</td>
</tr>
<tr>
<td>---</td>
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<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Severe thunderstorms and climate change.</td>
<td>Brooks, 2013</td>
<td>This study presented the current distribution of severe thunderstorms as a function of large-scale environmental conditions.</td>
<td>An analysis of the recent development of higher-resolution modeling techniques is discussed based on other environmental factors analyzed by other studies.</td>
<td>Climate model simulations suggest that in the future, CAPE will increase, and wind shear will decrease. A detailed analysis showed that the change in CAPE would lead to more frequent environments favorable for the development of severe thunderstorms. However, the high dependence on shear for tornado formation is still uncertain.</td>
</tr>
<tr>
<td>Climatic Role of North American Low-Level Jets on U.S. Regional Tornado Activity.</td>
<td>Weaver, Baxter, and Kumar, 2012</td>
<td>An investigation into the North American low-level jet (NALLJ) impact on April, May, and June (AMJ) severe weather variability.</td>
<td>The study assessed NALLJ variability between 1950-2010 based on an empirical orthogonal function (EOF) analysis. This EOF analysis relied upon seasonal anomalies of the AMJ meridional wind field at 850-hPa.</td>
<td>The study found a multidecadal variation in the strength of the NALLJ-tornado connection.</td>
</tr>
</tbody>
</table>
Table 8 continued.

<table>
<thead>
<tr>
<th>Is there an optimal ENSO Pattern that Enhances Large-Scale Atmospheric Processes Conducive to Tornado Outbreaks in the United States?</th>
<th>Lee et al., 2013</th>
<th>This study attempted to understand why tornadic activity in the US, during April and May (AM), have stronger correlations with the Trans Niño (TNI) index than with other ENSO indices.</th>
<th>This study uses both observational and modeling experiments to show a positive phase Trans Niño as a climate signal.</th>
<th>Experimental modeling showed how both warmer and cooler than normal sea-surface temperatures (SSTs) in the central tropical Pacific could work together in forcing a persistent and vigorous teleconnection pattern. This teleconnection pattern increased both the upper-level westerly and lower-level southwesterly winds over the central and eastern US. These winds advect drier and colder upper-level air from the high latitudes along with advecting warm Gulf of Mexico air towards the east side of the Rockies. Both the cold and warm wind advection help increase the lower-tropospheric and lower-level vertical wind shear which is conducive for intense tornadoes.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central American biomass burning smoke can increase tornado severity in the US.</td>
<td>Saide et al., 2015</td>
<td>An analysis of the effect of central American biomass burning on a historic severe weather outbreak that occurred on 27 April 2011.</td>
<td>This study focused on using the Weather Research and Forecasting (WRF-Chem) chemistry modeling system.</td>
<td>The analysis of the 27 April 2011 historical tornado outbreak showed that adding smoke to an environment already conducive to severe thunderstorm development could increase the likelihood of significant tornado occurrence. Numerical experimentation demonstrated that the presence of smoke lead to optical thickening of shallow clouds while soot enhanced the capping inversion through radiation absorption.</td>
</tr>
</tbody>
</table>
Recently, Kellner and Niyogi (2014) analyzed the spatial characteristics of tornado touchdown points regarding cities, population density, land use/land cover, and topography for the state of Indiana. The study concluded that a total of 61% of F0-F5 tornadoes and 43% of F0-F5 tornadoes touched down within 1 km of land use classified as either urban or forest. Additionally, tornado touch down points and population density were found to have a moderate to strong relationship. These findings document the possible role of land-use surface roughness on tornado occurrences (p. 2).

Observational studies that measure atmospheric thermodynamic available energy for storms and deep tropospheric shear help to provide a reasonable distinction between severe and non-severe storms (Brooks, 2013, p. 136). CAPE is expected to increase across the United States using the IPCC A2 Emissions scenario. This result is consistent with many theoretical predictions, like the theoretical predictions of a decrease in wind shear under the A2 climate scenario. Thunderstorms are thought to be the most readily available when CAPE and vertical wind shear both are significant in an environment (Trapp et al., 2007, p. 19721).

One outcome of a warmer climate is an increase in CAPE and a decrease in wind shear, which is a predominant signature of less organized, non-severe thunderstorms. When both CAPE and shear are evaluated together, the increase in CAPE compensates for the wind shear decrease, which still would produce an environment favorable for severe thunderstorm convection (Trapp et al., 2007, p. 19722). Current climate models suggest that an increase in CAPE will offset the decrease in wind shear, thus providing favorable environments for severe weather (Brooks, 2013, p. 136).
The National Academies of Sciences, Engineering, and Medicine report (2016) that CAPE, wind shear, and other relevant environmental factors are better observed having longer and more homogeneous records than do the individual severe convective storms themselves, resulting in many climate studies emphasizing large-scale variables. However, one caveat is that associations between these variables and the storms might change as climate does. “Also, the occurrence of severe weather is by no means guaranteed by a favorable large-scale environment; rather, it requires initiation by a preexisting disturbance of some kind, a process which appears less predictable and whose dependence on climate is not well understood (National Academies of Sciences, Engineering, and Medicine, 2016, p. 118-119).”

A few studies have attempted to use climate model projections to better estimate the overall effect an increase in greenhouse gas emissions will have on severe convective storm activity across the United States. Given the difficulty in simulating severe convection in low-resolution climate models, many of these recent studies focus on the large-scale environmental factors (e.g., CAPE and vertical wind shear) associated with severe convective storm activity instead of the individual severe convective storm cells themselves, a form of statistical downscaling. Nonetheless, given the limited number of studies which model the effect of increased greenhouse gas emissions on severe convective storms, it is probably the reason why detailed assessments of future projections of severe convective storm activity are not included in recent climate modeling reports (National Academies of Sciences, Engineering, and Medicine, 2016, p. 119-121).

Large atmospheric temperature increases from GHG emissions, causing flooding and increases in storm activity, and resulting in catastrophic global
climatological changes, have become known as “global warming” (Soon et al., 1999, p. 440). However, does this trend in global warming also hold true when addressing climate change at a regional level? Is it possible that global temperature trends mask substantial differences in regional temperature trends? Can an increase in storm activity and tornadoes be mainly a direct result of emission of air pollution within urban areas and increases in population size within metropolitan areas, as hypothesized in this study?
Chapter 9

METHODOLOGY

The research put forward in this thesis attempts to clarify the possible link between human induced anthropogenic forcing related to metropolitan areas and the physical mechanisms that occur naturally in thunderstorm and tornado development. This suggestive study is guided by the hypothesis that as metropolitan pollution increases, the probability of tornado occurrences also will increase. Its purpose is to extend to tornado causation present-day understandings of the link between human activity and a host of environmental effects, such as hurricanes, droughts, and floods, amongst a variety of others.

The unit of observation in this study is the metropolitan area, while the unit for analysis is the number of tornadoes in them for the year 2010. The information used in this report is from a merge of three machine-readable databases in which the common variable used to link them is the metropolitan area, as defined by the U.S. Census: “An area that includes a core urban area of 50,000 or more people, have at least one area of 50,000 or more people, plus adjacent territory that has a high degree of social and economic integration with the core as measured by commuting ties (United States Census Bureau Glossary, 2016).”

9.1 Population Data

The data available from the US Census Bureau initially included the three censuses for the years of 1990, 2000, and 2010. For several reasons, however, including the absence of information on key pollution data, the analysis uses only data from the year 2010. In the 2010 Census, the US Office of Management and Budgets adopted new standards to delineate the metropolitan statistical areas (MSA) from the
original standards used in 1990 and 2000, reclassifying the metropolitan statistical areas and changing the boundaries of their geographical areas. After assessing the original list of MSAs identified by the U.S. Census prior to the 2010 reclassification standards, several MSAs from 1990 and 2000 were no longer considered MSAs in 2010, so they could not be included for further analysis.

Looking at the population descriptive statistics of the MSAs identified in 2010, the majority of the MSAs fell within a positive and negative half standard deviation from the mean value. One positive half standard deviation from the mean was slightly more than 1,500,000 people. MSAs such as New York-Newark-Jersey City, NY-NJ-PA and Los Angeles-Long Beach-Anaheim, CA skewed the population histogram significantly to the right given their significantly higher population size in comparison to the other MSAs. To better control the skewness of the distribution while preserving their very large size, the largest MSAs were given a maximum population value of 1,500,000.

To make it resemble more closely a normal distribution, the 2010 population distribution of these MSAs is transformed using the inverse function, furthermore; due to the limitation of resources available to this research only 40 MSAs are included in the analysis. A total of 40 MSAs were selected using disproportional stratified random sampling to better ensure that estimates could be made with equal accuracy in different parts of the region, and so comparisons of sub-regions could be made with equal statistical power. Disproportional stratified sampling helped ensure that neither the smallest nor largest MSA populations were over represented, while helping to reduce any specific geographical region from being over represented within the analysis.
A random number generator was then used to select the MSAs randomly from a list of the entire population of MSAs in the country, stratified by plus or minus 3 standard deviations from the mean of the distribution of the population. Each standard deviation away from the mean represented a specific number of MSAs that were a proportion of the total number of MSAs available for 2010. For each MSA, the identification of the tornadoes involved using their x and y coordinates in conjunction with the ArcGIS tool that helped us to determine if the tornadoes had occurred inside a circle traced in a map around the geographical epicenter of the MSAs.

It should be noted that the 40 MSAs were not solely selected due to pollution constraints, but also due to the available personal time and resource constraints of the researcher. This thesis began during the Fall 2014 semester as a proposal, before approval was given during the Spring 2014 semester to complete as a master’s level thesis. This research was put on hold while an MBA degree was completed at the University of Delaware from 2014 through 2016. It was not until Summer 2016 when the work on this thesis restarted. Initially, this research was going to include all the MSAs available for 2010. However, given the significant time lapse and pending degree conferral, the decision was made to consolidate and streamline the design of this study.

9.2 Environmental Protection Agency (EPA) Pollution Data

The pollution dataset came from the United States Environmental Protection Agency’s Air Quality System (AQS) database (U.S. Environmental Protection Agency Air Data, n.d.). The pollution data is extracted for the year 2010, to stay consistent with the population data. This EPA dataset included ozone (O₃), carbon monoxide (CO), particulate matter with a diameter of 2.5µ, particulate matter with a diameter of
10µ, nitrogen dioxide (NO₂), sulfur dioxide (SO₂), and lead (Pb) (see Table 9). These pollutants correspond to the criteria gases and the particulate matter that various EPA monitoring stations across the US record on a daily and yearly basis. A filter was applied to the raw data extract based on MSA specific pollution data. The AQS database provided at least one pollution monitoring station per MSA regarding ozone concentrations. “An AQS site is a distinct geographic location that has one or more monitors. Not every site measures the same parameters (U.S. Environmental Protection Agency Air Data, n.d.).” Unfortunately, given that limited nature of the available pollution monitoring station, one station represented the entire geographic boundary of an MSA. It represents an important potential weakness of this study.

Table 9: Pollutants that the EPA monitors on a daily, monthly, and yearly basis, together with their unit of measurement and the EPA monitoring standard for each measured pollutant.

<table>
<thead>
<tr>
<th>Pollution Measurement</th>
<th>Unit of Measurement</th>
<th>EPA Monitoring Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ozone (O₃)</td>
<td>Parts per million (ppm)</td>
<td>8hr. Run Average</td>
</tr>
<tr>
<td>Sulfur Dioxide (SO₂)</td>
<td>Parts per billion (ppb)</td>
<td>3hr. Bulk Average</td>
</tr>
<tr>
<td>Nitrogen Dioxide (NO₂)</td>
<td>Parts per billion (ppb)</td>
<td>1hr. Pollutant Standard</td>
</tr>
<tr>
<td>Carbon Monoxide (CO)</td>
<td>Parts per million (ppm)</td>
<td>8hr. Run Average</td>
</tr>
<tr>
<td>Particulate Matter 10 micrometers (PM₁₀)</td>
<td>Micrograms/Cubic Meters (LC)</td>
<td>24hr. Bulk Average</td>
</tr>
<tr>
<td>Particulate Matter 2.5 micrometers (PM₂.₅)</td>
<td>Micrograms/Cubic Meters (LC)</td>
<td>24hr. Bulk Average</td>
</tr>
</tbody>
</table>
From the list of 40 cities identified for inclusion in the analysis, only 18 had enough pollution data available (see Table 10). 22 of the original cities were replaced with other cities that had the required pollution data from the population of 347 MSAs. They were randomly selected as before, and their sample stratified by 3 positive and negative standard deviations.

Table 10: Replacing MSAs which lacked adequate EPA pollution data. Replaced MSAs are crossed out in red. Those in yellow are included in the analysis. This is a small sample of the MSAs used for analysis.
Ozone was the only pollutant available for each of the 40 cities. In addition, the EPA’s outdoor air quality dataset and carbon dioxide information were also available from the EPA’s Greenhouse Gas Reporting Program (GHGRP). The GHGRP provides carbon dioxide emission data during 2010 for each reporting facility within each MSA. Carbon dioxide is reported in CO$_2$ equivalents (CO$_2$E) (U.S. Environmental Protection Agency Greenhouse Gas Reporting Program, n.d.). The next two tables (Tables 11 and 12) show, respectively, the extent of incompleteness of the pollution data for the MSAs, and the final list of MSAs used in this study. As previously reported, ozone was the only pollutant all 40 MSAs had recorded in 2010.

Table 11: Shows the inadequate pollution data for the original list of 40 MSAs. Ozone was the only pollutant that every MSA recorded during 2010.

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Proportion</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>32.5%</td>
</tr>
<tr>
<td>PM$_{10}$</td>
<td>50.0%</td>
</tr>
<tr>
<td>PM$_{2.5}$</td>
<td>87.5%</td>
</tr>
<tr>
<td>O$_3$</td>
<td>100.0%</td>
</tr>
<tr>
<td>NO$_2$</td>
<td>47.5%</td>
</tr>
<tr>
<td>SO$_2$</td>
<td>62.5%</td>
</tr>
<tr>
<td>Pb</td>
<td>10.0%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Proportion</th>
</tr>
</thead>
<tbody>
<tr>
<td>13 have data</td>
<td>32.5%</td>
</tr>
<tr>
<td>27 do not have data</td>
<td>67.5%</td>
</tr>
<tr>
<td>20 have data</td>
<td>50.0%</td>
</tr>
<tr>
<td>20 do not have data</td>
<td>50.0%</td>
</tr>
<tr>
<td>35 have data</td>
<td>87.5%</td>
</tr>
<tr>
<td>5 do not have data</td>
<td>12.5%</td>
</tr>
<tr>
<td>40 have data</td>
<td>100.0%</td>
</tr>
<tr>
<td>0 do not have data</td>
<td>0.0%</td>
</tr>
<tr>
<td>19 have data</td>
<td>47.5%</td>
</tr>
<tr>
<td>21 do not have data</td>
<td>52.5%</td>
</tr>
<tr>
<td>25 have data</td>
<td>62.5%</td>
</tr>
<tr>
<td>15 do not have data</td>
<td>37.5%</td>
</tr>
<tr>
<td>4 have data</td>
<td>10.0%</td>
</tr>
<tr>
<td>36 do not have data</td>
<td>90.0%</td>
</tr>
</tbody>
</table>
Table 12: A side by side comparison of the original list of 40 MSAs (left) and the list with replaced MSAs (right).

<table>
<thead>
<tr>
<th>40 Cities for Analysis</th>
<th>New Cities for Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Great Falls, MT</td>
<td>Ames, IA</td>
</tr>
<tr>
<td>Parkersburg-Vienna, WV</td>
<td>Parkersburg-Vienna, WV</td>
</tr>
<tr>
<td>Fond du Lac, WI</td>
<td>Munice, IN</td>
</tr>
<tr>
<td>Longview, WA</td>
<td>Birmarck, ND</td>
</tr>
<tr>
<td>Ocean City, NJ</td>
<td>Michigan City-La Porte, IN</td>
</tr>
<tr>
<td>Kankakee, IL</td>
<td>Altoona, PA</td>
</tr>
<tr>
<td>Barnstable Town, MA</td>
<td>El Centro, CA</td>
</tr>
<tr>
<td>Florence, SC</td>
<td>Yuba City, CA</td>
</tr>
<tr>
<td>Appleton, WI</td>
<td>Appleton, WI</td>
</tr>
<tr>
<td>Grand Junction, CO</td>
<td>Napa, CA</td>
</tr>
<tr>
<td>Johnstown, PA</td>
<td>Johnstown, PA</td>
</tr>
<tr>
<td>Terre Haute, IN</td>
<td>Terre Haute, IN</td>
</tr>
<tr>
<td>Wheeling, WV-OH</td>
<td>Morgantown, WV</td>
</tr>
<tr>
<td>Racine, WI</td>
<td>Farmington, NM</td>
</tr>
<tr>
<td>Pittsfield, MA</td>
<td>Springfield, OH</td>
</tr>
<tr>
<td>Iowa City, IA</td>
<td>Lake Charles, LA</td>
</tr>
<tr>
<td>Bangor, ME</td>
<td>Fargo, ND-MN</td>
</tr>
<tr>
<td>Las Cruces, NM</td>
<td>Las Cruces, NM</td>
</tr>
<tr>
<td>Pensacola-Ferry Pass-Brent, FL</td>
<td>Pensacola-Ferry Pass-Brent, FL</td>
</tr>
<tr>
<td>Gulfport-Biloxi-Pascagoula, MS</td>
<td>Lancaster, PA</td>
</tr>
<tr>
<td>Lincoln, NE</td>
<td>Little Rock-North Little Rock-Conway, AR</td>
</tr>
<tr>
<td>Asheville, NC</td>
<td>Youngstown-Warren-Boardman, OH</td>
</tr>
<tr>
<td>Greensboro-High Point, NC</td>
<td>Greensboro-High Point, NC</td>
</tr>
<tr>
<td>Corpus Christi, TX</td>
<td>Corpus Christi, TX</td>
</tr>
<tr>
<td>Lafayette, LA</td>
<td>Evansville, IN-KY</td>
</tr>
<tr>
<td>Montgomery, AL</td>
<td>Akron, OH</td>
</tr>
<tr>
<td>Syracuse, NY</td>
<td>Syracuse, NY</td>
</tr>
<tr>
<td>Springfield, MO</td>
<td>Springfield, MO</td>
</tr>
<tr>
<td>Boise City, ID</td>
<td>Charleston, WV</td>
</tr>
<tr>
<td>Fayetteville, NC</td>
<td>Fayetteville, NC</td>
</tr>
<tr>
<td>Peoria, IL</td>
<td>Beaumont-Port Arthur, TX</td>
</tr>
<tr>
<td>Anchorage, AK</td>
<td>Fort Wayne, IN</td>
</tr>
<tr>
<td>New York-Newark-Jersey City, NY-NJ-PA</td>
<td>New York-Newark-Jersey City, NY-NJ-PA</td>
</tr>
<tr>
<td>Hartford-West Hartford-East Hartford, CT</td>
<td>Hartford-West Hartford-East Hartford, CT</td>
</tr>
<tr>
<td>Baltimore-Columbia-Towson, MD</td>
<td>Baltimore-Columbia-Towson, MD</td>
</tr>
<tr>
<td>Salt Lake City, UT</td>
<td>Salt Lake City, UT</td>
</tr>
<tr>
<td>Riverside-San Bernardino-Ontario, CA</td>
<td>Riverside-San Bernardino-Ontario, CA</td>
</tr>
<tr>
<td>Greenville-Anderson-Mauldin, SC</td>
<td>Albuquerque, NM</td>
</tr>
<tr>
<td>Charlotte-Concord-Gastonia, NC-SC</td>
<td>Charlotte-Concord-Gastonia, NC-SC</td>
</tr>
<tr>
<td>Kansas City, MO-KS</td>
<td>Kansas City, MO-KS</td>
</tr>
</tbody>
</table>
9.3 Historical Weather Data

Weather Warehouse (Weather Warehouse, n.d.) provided historical weather data by month. Given the limited nature of pollution data, pollution-monitoring stations were not the same stations from which the meteorological data is collected. Regardless, this analysis assumes that the EPA stations and the Weather Warehouse stations are in close enough proximity that the pollution and weather conditions within their respective metropolitan statistical areas are the same.

Weather Warehouse recorded variables included lowest temperature (°F), highest temperature (°F), warmest minimum temperature (°F), coldest maximum temperature (°F), average minimum temperature (°F), average maximum temperature (°F), mean temperature (°F), and total precipitation (inches). These variables were averaged monthly for the year 2010 (Weather Warehouse 2017). One potentially key variable that was not recorded using Weather Warehouse monitoring stations, was measures that could be used to depict moisture levels. To extract some type of moisture measurement, Weather Underground historical weather made available dew point values (°F).

Again, this analysis assumes that the Weather Underground stations were within the metropolitan statistical area city limits, and that the stations can be used to approximate moisture levels for each MSA (Weather Underground, n.d.). Using Weather Underground historical weather information averaged monthly for 2010, information was collected on maximum dew point temperature (°F), minimum dew point temperature (°F), and mean dew point temperature (°F) (Weather Underground 2017). Dew point temperature indicates the temperature at which air needs to be cooled for saturation to occur.
A better measurement of moisture within the air is relative humidity, which is a ratio of actual vapor density and saturated vapor density, expressed as a percentage (Relative Humidity, 2014). While relative humidity cannot be directly measured, or monitored, McNoldy (2017) recently found a way to calculate an approximate value for relative humidity using the August-Roche-Magnus approximation. Using this converter, an approximate relative humidity percentage was calculated for each month in 2010, using dew point temperatures from Weather Underground, and air temperatures from Weather Warehouse.

After compiling the pollution, population, and meteorology data into an Excel spreadsheet, it became apparent that a few stations reported recordings that seemed erroneous for the months of January, February, March, October, November, and December. Fortunately, this was not the case for data recorded between the months of April thru September, which coincides with severe thunderstorm climatology. Consequently, for purpose of this analysis, and to ensure that none of the 40 cities had important information missing or in error, the pollution and weather data for each of the 40 cities were aggregated for the months between April and September 2010, inclusive, and used in the analysis.

9.4 ArcGIS Tornado Touchdown Points

The analysis required the identification of the tornadoes that had occurred in each of the MSAs. To accomplish this step, this research used the tornado touchdown points provided by the National Oceanic Atmospheric Administration (Storm Prediction Center, 2001). It is a dataset with tornado geographical touchdown points from 1950 to 2011 mapped along with population density for the year 2000 as shown in Figure 1. To be consistent with the population data set provided by the US Census
Bureau, used here are only the tornadoes occurring during the entire year of 2010 (see Figure 2).

Figure 1: ArcGIS shape file depicting all Continental US tornado touchdown points, 1950-2011 along with population density for the year 2000 (Storm Prediction Center, 2001).
Figure 2: GIS depiction of tornado reports and tracks for 2010, National Weather Service. During 2010, an EF5 tornado was not recorded within the continental United States (Storm Prediction Center, 2001).

The Storm Prediction Center (SPC) dataset is in a shapefile that contains all the necessary points to create a tornado layer in ArcGIS to show where tornadoes touched down in relation to the location of MSAs. The next ArcGIS image provides a visual depiction of the number of tornadoes that touched down in the 40 metropolitan areas. The 1282 tornadoes included in the study are only those that touched down inside the circles of the 40 metropolitan areas in the study; excluded from further analysis are tornadoes that did not affect any of the areas of the 40 cities.
From Figure 2, 1282 tornadoes were recorded during 2010, with no EF5 tornadoes being recorded. During 2010, there were 13 EF4 tornadoes, 32 EF3s, 127 EF2 tornadoes 341 EF1 tornadoes, and 769 EF0 tornadoes. Many of the recorded tornadoes occurred within the southeast region of the United States, along with many occurring across the Midwest and Ohio River Valley. As anticipated, many tornadoes were recorded within “Tornado Alley” with Minnesota having 113 recorded tornadoes, Texas having 107 tornadoes, and Oklahoma having 102 tornadoes. 2010 had the 8th highest number of tornadoes out of the last 60 years (1952-2011), with 44 states having at least 1 tornado occurrence. Figures 3 and 4 show the results of the ArcGIS analysis combining metropolitan statistical areas with tornado touchdown points occurring in them (Storm Prediction Center, 2001).

The MSA GIS data layer used for this analysis was pre-loaded into ArcGIS by the U.S. Census Bureau and was available for public use. Each of the brown shaded MSAs were delineated by the U.S. Census Bureau based upon their 2010 definition of an MSA. Figure 3 maps the tornado touchdown points for 2010 on top of the layer that shows every delineated MSA available. Figure 4 captures only the 40 MSAs identified for further analysis along with the corresponding tornado touchdown points for 2010. In order for a tornado touchdown point to be considered, the tornado had to have touched down within the MSA boundary identified by the U.S. Census Bureau. If a tornado touchdown occurred outside of the MSA boundaries, it was not included in further analyses. Tornado touchdown points occurring outside an MSA, and then crossing through the MSA boundary were not included, given that the tornado formed prior to any ecological impact associated with the MSA in question.
Figure 3: Tornado touchdown points and tracks within MSAs, GIS Image. National Weather Service 2010. Tornados with an Enhanced Fujita scale intensity of 0 are dark green. Light green depicts EF1 tornadoes; yellow depicts EF2 tornadoes, orange shows EF3 tornados, while red shows EF4 tornadoes. The brown color represents all of the MSAs identified by the U.S. Census Bureau.
Figure 4: A GIS image of the map that plots tornado touchdown points and tracks. Data from the National Weather Service, 2010. The counties shaded with color represent the MSAs used for this analysis. Tornadoes with an Enhanced Fujita scale intensity of 0 are dark green. Light green depicts EF1 tornadoes; yellow depicts EF2 tornadoes, orange shows EF3 tornadoes, while red shows EF4 tornadoes.

Looking at Figure 4, many tornadoes occurred within “Tornado Alley.” From the figures above and using just the naked eye, it can be seen that many tornadoes did touchdown within many of the MSAs used for this analysis. Some of the MSAs had multiple tornadoes touchdown with the MSA boundary. In accordance with the hypothesis put forth regarding MSA pollution inducing tornadoes, Little Rock, AR preliminarily showed the effect of tornadoes forming downwind of the MSA boundary, with tornadoes moving in the northeast direction from the southwest. Theoretically, tornadoes should touchdown northeast of the city limit due to their
typical southwest to northeast movement. Some additional speculations arise from the MSAs in Indiana, Ohio, and North Carolina. As predicted, tornado touchdowns are less frequent west of the Rocky Mountains. It should also be noted that “Dixie Alley” seemed to have a high frequency of tornadoes during 2010.

In summary, using EPA, NOAA, and US Census data, 40 MSAs were randomly selected for analysis. Initially, many of the randomly selected cities were replaced because they lacked sufficient pollution data which would be needed in testing the hypothesis. Using the EPA pollution data, ozone data was the selected pollutant, for each of the 40 MSAs during 2010. Using a GIS data layer that plotted counties, an additional filter was used to highlight just the select 40 MSAs needed for analysis. Using a base map at the county level, the NOAA 2010 tornado touchdown points were plotted on top to see where the points were distributed with respect to the MSAs. Some MSAs depicted tornado touchdown points northeast and downwind of the city, helping to give preliminary support to the hypothesis of MSA pollution inducing tornadoes.

9.5 SPSS LS (Linear) Regression Analysis

The applicable data for each city was analyzed using IBM SPSS. The complete set of variables selected to test the hypothesis put forth included total population of the statistical area, ozone pollution levels, relative humidity, average minimum temperature, average maximum temperature, mean temperature, total precipitation, geographical location of the MSAs, whether located in tornado alley (region including central Texas, northward into North Dakota), CO₂ emissions, and the number of tornadoes that occurred within each MSA. The temporal period for the analysis was from April to September during 2010.
The hypothesis guiding this study assumes that human urban conglomerates indirectly influence temperatures. Running a few exploratory multiple linear regressions (not shown) it became apparent that using mean temperature as the sole temperature measurement variable was sufficient. In theory, average mean temperature accounts for any change in the scores of average maximum and minimum temperatures. Logically, when average maximum temperature increases, the average minimum temperature increases as well. Table 13 provides a brief description of the variables used in the SPSS multiple linear regression model.

Table 13: Description of the variables used in the analysis along with descriptive statistics.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Range</th>
<th>Maximum</th>
<th>Minimum</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population</td>
<td>The populations of each of the 40 MSAs used for analysis.</td>
<td>1410458</td>
<td>1500000</td>
<td>89542</td>
<td>507220.73</td>
<td>468526.59</td>
</tr>
<tr>
<td>Ozone</td>
<td>The air pollutant available from the EPA for all 40 MSAs.</td>
<td>.01</td>
<td>.04</td>
<td>.03</td>
<td>.032</td>
<td>.0035</td>
</tr>
<tr>
<td>Mean Temperature</td>
<td>The average daily temperature.</td>
<td>23.50</td>
<td>83.98</td>
<td>60.48</td>
<td>70.59</td>
<td>5.82</td>
</tr>
<tr>
<td>Tornado Alley</td>
<td>The geographical location for the MSAs. MSAs received “0” if they did not fall within Tornado Alley, “1” if they did.</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>.65</td>
<td>.48</td>
</tr>
</tbody>
</table>
Table 13 continued.

<table>
<thead>
<tr>
<th>CO₂ Emissions</th>
<th>CO₂ emissions recorded by the EPA, using facility specific emission data within each MSA.</th>
<th>40597771</th>
<th>40597779</th>
<th>8</th>
<th>6042690.87</th>
<th>10574975.7</th>
</tr>
</thead>
</table>

Total Number of Tornadoes during 2010 1,282 (Tornadoes occurred in all but 4 of the lower 48 – Delaware, Rhode Island, Massachusetts, and Nevada).

Least square multiple linear regression analysis of the number of tornadoes was done using all five predictors. They included population, mean temperature, ozone, CO₂ emissions, and tornado alley. This model served as a benchmark to compare the performance of the various other preliminary multiple linear regression models (not shown, available upon request.). The results showed that the population variable had the largest positive effect. However, looking at its histogram, the data showed positive skewness. Consequently, the population variable squared root transformation is used in the linear regressions to reduce skewness (see Figure 5).
To compare the effect of the pollution predictor variable on the number of tornadoes in 2010, the ozone predictor variable was replaced with the \textit{log base 10 transformation of CO}_2 \textit{emissions} while including the other variables in the model. The transformed ozone variable improved the effect of ozone in predicting the number of tornadoes occurring within the metropolitan statistical areas. The preliminary analysis also included investigating the appropriateness of using the two pollution variables together rather than just having one. The initial model included as predictors tornado alley location, mean temperature, square root of the population, ozone, and log base 10
of the CO₂ emissions variables. The results showed the presence of a statistically
significant first order multiplicative interaction effect between CO₂ emissions and
mean temperature. After these preliminary models were done, the final multiple linear
regression model of the number of tornados used in this study included an A.
interaction term between CO₂ emissions and mean temperature, B. location in tornado
alley, C. mean temperature, D. square root of population, E. ozone, and F. log base 10
of CO₂ emissions.
10.1 Preliminaries to the results of this study

The United States Census Bureau in 2010 published a few statistics about Urban Areas in the US, which are as follows: 71.2% Percent of U.S. population living within Urbanized Areas; 80.7% of the U.S. population that is urban. There were 2,534.4 persons per square mile. The 2010 Census reported the population of the US to be approximately 308.7 million people, which increased 9.7% from the 2000 Census population of 281.4 million. Figure A.56 (see appendix) shows the US population change from 1950 to 2010.

The increase of 9.7% was slightly lower than the population change from 1990 to 2000. At the regional level, from 2000 to 2010, the increase was much faster in the South and West, as compared to the Midwest and Northeast. The growth in the South was 14.3 while the rise in the West was 13.8. Likewise, the increase in the Midwest was 3.9 percent while the increase in the Northeast was 3.2 percent (Mackun, Wilson, Fischetti, and Gоворowsка, 2011, p. 1-2). Figure A.57 (see appendix) depicts which states correspond to each region in the US. Table A.3 shows the population change for the United States, each of its regions, and by each state. The southern region increased by 14.3 million people over the decade to a total of 114.6 million people. The West grew by 8.7 million people to a total of 71.9 million people. The Midwest grew by 2.5 million people to a total of 66.9 million people, while the Northeast grew by 1.7 million people to a total of 55.3 million people (Mackun et al., 2011, p. 3).

In 2010, over four-fifths (approximately 83.7 percent) of the US population lived within 366 of the nation's metro areas, and another one-tenth (10.0 percent) of
the population resided in the nation’s 576 micro areas. The metro areas grew by 10.8 percent, which is almost double the increase of the micro areas (5.9 percent).

Population growth of at least two times the national rate occurred in many of the micro and metro areas. Table A.4 shows the populations of the metro and micro statistical areas for 2000 and 2010 while Figure A.58 (see appendix) displays the percentage change for metro and micro statistical areas. Many of the fast-growing micro areas are close to the fastest growing metro areas. However, many of the slow-growing or declining micro-areas are located in proximity to declining or slow-growing metro areas. Figure A.59 (see appendix) shows the population and percentage change from 2000 until 2010. Figure A.60 (see appendix) shows overall distribution for the US during 2010 by county. Finally, Figure A.61 (see appendix) displays county population density across the US in 2010 (Mackun et al., 2011, p. 1-10).

10.2 The analysis of the impact of population on tornado occurrence

A multiple linear regression analysis for the Full Model (Model #4) predicting the number of tornadoes occurring in 2010 based on the previously enumerated six predictors, accounted for 38% of the variance of the number of tornadoes. The model was statistically significant (F = 3.372, significant at p < .05). Table 14 shows the results of the preliminary multiple linear regression.
Table 14: SPSS output for all multiple regression models used with the analysis.

<table>
<thead>
<tr>
<th></th>
<th>Full Model</th>
<th>Partial Model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unstandardized</td>
<td>Standardized</td>
</tr>
<tr>
<td></td>
<td>Coefficients (B)</td>
<td>Coefficients (β)</td>
</tr>
<tr>
<td></td>
<td>t-statistic</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Significance</td>
<td></td>
</tr>
<tr>
<td>(Constant)</td>
<td>-13.439</td>
<td>-1.186</td>
</tr>
<tr>
<td></td>
<td>-.244</td>
<td>2.498</td>
</tr>
<tr>
<td></td>
<td>.602</td>
<td></td>
</tr>
<tr>
<td>SQRTPop.</td>
<td>.004</td>
<td>.494</td>
</tr>
<tr>
<td>TornadoAlley</td>
<td>1.072</td>
<td>.236</td>
</tr>
<tr>
<td>AprilSeptO3</td>
<td>-176.835</td>
<td>-.284</td>
</tr>
<tr>
<td>AprilSeptTemp</td>
<td>.249</td>
<td>1.584</td>
</tr>
<tr>
<td>Log.CO2</td>
<td>3.003</td>
<td>1.752</td>
</tr>
<tr>
<td>CO.MeanTemp</td>
<td>-.042</td>
<td>2.964</td>
</tr>
<tr>
<td></td>
<td>.494</td>
<td></td>
</tr>
<tr>
<td></td>
<td>.290</td>
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<td></td>
<td>.004</td>
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</tr>
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<td></td>
<td>.123</td>
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<tr>
<td></td>
<td>.019</td>
<td></td>
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<tr>
<td></td>
<td>.052</td>
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<td></td>
<td>.524</td>
<td></td>
</tr>
<tr>
<td></td>
<td>.3407</td>
<td></td>
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<td></td>
<td>.002**</td>
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<td>.019</td>
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<td></td>
<td>.052</td>
<td></td>
</tr>
<tr>
<td></td>
<td>.352</td>
<td></td>
</tr>
<tr>
<td></td>
<td>.727</td>
<td></td>
</tr>
<tr>
<td>R²</td>
<td>.380*</td>
<td>.334**</td>
</tr>
<tr>
<td>Std. Error of</td>
<td>1.879</td>
<td>1.891</td>
</tr>
<tr>
<td>Regression</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Assessing the tolerance values for each of the values in the Partial Model show that the tolerance for SQRTPop, TornadoAlley, AprilSeptO3, and AprilSeptTemp were .805, .924, .874, and .886 respectively. These values indicate that multicollinearity does not pose an issue with most of the predictors, except tornado alley. A note on the levels of significance of the predictors is appropriate here. Since the study is exploratory and the number of cities included in the analysis is so small (40), the p>=.05 practice was not used. Instead, the table reports the actual “p’s” for each of the predictors. As shown in the full model, the findings show that as predicted, the number of tornadoes increase with increases in the size of the population.
(SQRTPop); if they occurred in tornado alley; with increases in the average temperature between April to September of 2010; and with increases in CO$_2$ ($\log_{10}$CO$_2$). The two interaction terms (AprilSeptO3 and CO2MeanTemp) have negative signs. While these interactive multiplicative effects were not included in the initial predictions, future research should clarify what they may mean. Overall, the findings are very suggestive of the importance of anthropogenic effects on the occurrence of tornadoes, as predicted by Aguirre et al., (1993) as well as other researchers.

**10.3 Further Discussion**

The purpose of this analysis is not to challenge “thermodynamic theory” or the “standard model,” but rather to build upon the work of Aguirre et al., (1993) that called for further examination of the link between human ecological patterns and tornado occurrence. The results from that study showed that urban areas with highly dense population centers had a higher probability of tornado occurrence than did surrounding rural areas and that this well-known effect was not spurious, “the result of more eyes in the sky,” as has been commonly understood. Aguirre et al., (1993) was also able to reference other studies showing how human activities on the surface of the earth impacted tornadogenesis. It was built upon the narrative of incorporating general sociological theory into disaster studies, along with developing a better understanding of how the occurrence and effect of hazards respond to the social and physical ecological adjustments of human populations (p. 623). This present study continues to examine the role humans have on their surrounding environment but uses more appropriate measurement variables. Where Aguirre et al., (1993) used the county level as a unit of analysis, this study uses Metropolitan Statistical Areas as the unit of
analysis (p. 630), a better variable that reduces the potential occurrences and impacts of the ecological fallacy. It also used a direct measurement of pollution that is absent in the previous study.

**10.4 Urbanization as the link between human activities and tornadogenesis**

The untested set of mechanisms providing the rationale for this study is as follows: a. Urban populations are increasing but available land is finite; b. As populations increase in finite areas, they begin to urbanize further away from city centers, encouraging the transition from rural land to a more urbanized landscape; c. As the natural environment begins to be reshaped, the microclimate is indirectly being altered; and d. The increase in tornado touchdowns is a result of these eugenic-induced changes in microclimates that increase the energy available to tornadic storms and may facilitate their occurrence if other well-known factors in the standard model of tornado occurrence are in place. In the rest of this study, the focus shifts to a greater consideration of the ecological impacts of urbanization.

The present study attempted to isolate the impact on tornado formation of pollution associated with human ecological patterns and with urbanization and sprawl. The results from this study show congruence with Stone (2008). While this study only accounted for MSA O₃ concentrations for just 2010, Stone (2008) integrated a published sprawl index from Ewing, Pendall, and Chen (2003), which used 45 major US cities over a 13-year period (p. 691-692). His study found that large US cities, which experienced higher levels of urban sprawl, or more urban sprawl-like characteristics, observed higher levels of O₃ concentrations, higher O₃ precursor emissions, and more O₃ exceedance days (Stone, 2008, p. 693-695).
Similarly, Bereitschaft and Debbage (2013) ran 60 linear regression models to assess potential associations between measures of urban form/urban sprawl and the concentrations of O₃, VOCs, NOₓ, PM₂.₅, and CO₂ between 1998 and 2002. As expected, the study found several statistically significant associations between urban form/urban sprawl and pollution concentration/emission of air pollutants detectable at the MSA level. Their results concluded that metropolitan areas that experienced lower levels of sprawl exhibited lower concentrations of O₃ and PM₂.₅. Metropolitan areas that experienced the highest levels of sprawl recorded some of the highest average concentrations of O₃ and PM₂.₅ (p. 622-27). They also hypothesized that the largest and most dense metropolitan areas should show lower levels of O₃ concentrations than the largest and most sprawling cities, which should exhibit higher O₃ concentrations. Figure 6 from Bereitschaft and Debbage (2013) depicts sprawl and O₃ concentrations. New York, Chicago, and Seattle have dense urban centers showing lower O₃ concentrations compared to sprawling cities like Atlanta, areas east of Los Angeles, and Houston (p. 626). Bereitschaft and Debbage (2013) also found urban continuity and shape complexity to be significantly associated with air pollution emissions (p. 623). This study did not account for individual MSA landscape metrics, which may have resulted in ozone concentrations varying within individual cities rather than varying by region.
Figure 6: O$_3$ concentrations (average annual fourth maximum eight-hour) between 1998 and 2002 for (a) Atlanta, GA; (b) New York, NY; (c) Chicago, IL; (d) Los Angeles, CA; (e) Houston, TX; and (f) Portland, OR. The red color depicts the highest O$_3$ concentrations, while the dark blue color represents the lowest O$_3$ concentrations. For large US metropolitan cities, the highest O$_3$ concentrations were found in the suburbs of the urban center (Bereitschaft and Debbage, 2013, p. 625).

Using the top sprawling cities and top compact cities identified by Ewing et al. (2003), the ArcGIS map used in this analysis shows that the most sprawling cities are located across the southeast and the lower Midwest, while most of the compact cities
are across the northeast and upper Midwest. Housing density from 1980 until 2030 depicted in Figure A.20 supports the narrative that metropolitan areas are in fact sprawling away from city centers. These observations are also in agreement with Figures A.21- A.23, which depict the extent of rural areas in the US from 1980 to 2020. Areas across the Northeast and Midwest are becoming less rural as expected, although the largest transition from rural to urban spans across the Southeast, Ohio River Valley, and the lower Mississippi River Valley.

These observations also agree with the findings from Brown et al., (2005). These authors concluded that during 1950-2000, extra-urbanized areas grew sevenfold in transitional metropolitan counties, while growing nearly tenfold for counties adjacent to metropolitan areas. Additionally, after further land change analysis of the South-eastern eco-region, the study found significant rates of change for both the Atlantic Coast Pine Barrens and the Northern Piedmont eco-regions (Figure 7). Within these specific eco-regions, large urban growth occurred due to an extension of transportation systems and the emerging of beltway cities (p. 1854-1860).
Figure 7: Land cover changes occurring in the South-eastern eco-region between 1973 and 2000. The pie chart represents the types of land transformations. The inset graph represents overall change (Brown et al., 2005, p. 1854-1860).

This analysis only accounts for 2010. Boruff et al., (2003) was able to find tornado hazard density patterns over the last several decades. The 1990s (Figure 8) showed tornado hazard high density patterns in the Great Plains, stretching from coastal Texas to South Dakota, along the Gulf Coast, and over the entire state of Florida. Coastal counties along the Mid-Atlantic (especially North Carolina and
Virginia) also showed clear and distinguishable tornado hazards from earlier decades (p. 111).

Figure 8: Tornado density hazards for the 1990s (Boruff et al., 2003, p. 114).

As this analysis suggests, MSAs and regions that experienced or are currently experiencing the highest rates of sprawl seem to coincide with the tornado density patterns found over the last several decades, especially across the southeast and lower
Midwest. Boruff et al., (2003) showed significant depopulation over the past half-century across the Great Plains, lower Mississippi Valley, and Appalachia regions. They speculate that the population changes in these areas help to partially explain the hazard density changes across the US (p. 114).

The population variable was consistently significant within the various linear regression models. A recent study confirmed the effect population has on the frequency of reported tornadoes. Specifically, if more (less) people are located within an area, more (less) tornado reports will result (Anderson, Wikle, Zhou, and Royle, 2007, p. 571) However, Aguirre et al., (1993) affirmed that the association between population and tornado reporting is spurious. They found that size of population was not a statistically significant predictor of the occurrence of F1 tornadoes, the weakest and more prone tornado to escape being noticed by official channels, and thus more dependent for identification by the “eyes on the sky” effect alluded by some. For the entire US, there is little or no significant correlation between tornado hazard density and population density for any decade, partially explained by counties that do not experience tornado hazards altogether (Boruff et al., 2003, p. 114). However, the size of populations should not be disregarded. Not everything is settled. For example, Kellner and Niyogi (2014) reported that their buffer analysis showed a large percentage of total tornado touchdown points in areas with low population densities (p. 28).

Tornado Alley was another variable used in the analysis, but, to our surprise, was only statistically significant when the model used CO₂ emissions rather than O₃ concentrations. The linear regression treated the tornado alley variable as MSAs either being located in tornado alley or not, in order to see if MSAs within tornado alley had
more tornado touchdowns during 2010. However, tornado occurrences are very infrequent west of the Rockies (Boruff et al., 2003, p. 109) and having a half dozen MSAs west of the Rockies may have hindered the significance of this variable.

When the ozone variable was replaced by CO₂ emissions, the pollution variable became insignificant in all of the linear regression models. Yet, in theory, CO₂ emissions should be increasing with larger populations and more sprawl. Grimm et al., (2008) argues that urban centers have higher CO₂ emissions resulting from dense concentrations of industry, production, consumption, waste disposal and transportation acting as point sources of CO₂ emissions; specifically, the 20 largest US cities ever year contribute more CO₂ to the atmosphere that the total land area of the US is capable of absorbing (p. 757-759).

Interestingly, Glaeser and Kahn (2010) noted that urban development in the US tends to occur within low density areas prone to very hot summers. They concluded that areas with the lowest CO₂ emissions were generally in California, while areas in Texas and Oklahoma experienced the highest CO₂ emissions. Additionally, they found a strong negative association between land use regulations and CO₂ emissions, suggesting that new development is pushed by regulations away from cities, towards nearby less regulated areas of higher emissions. Likewise, they concluded that cities had significantly less CO₂ emissions compared to surrounding suburban areas, and that the largest city-urban gap exists for very old cities (p. 404).

When accounting for just CO₂ emissions from on-road sources, Bereitschaft and Debbage (2013) found that only residential density was significantly associated with CO₂ emissions. The more urban areas increased in their residential density, the less CO₂ emissions from on-road vehicles large MSAs could expect. At the same time,
they found that increases in the metropolitan population was also significantly associated statistically with an increase in CO\textsubscript{2} emissions from on-road vehicles. In terms of overall land area, large metropolitan areas were associated with an increase in CO\textsubscript{2} emissions, but the increase was far less important than the increases in CO\textsubscript{2} emissions caused by increases in population (p. 628-629).

In this study, when both O\textsubscript{3} and CO\textsubscript{2} were included together in the regression model there was no significance in either variable, and mean temperature remained insignificant. What was interesting was that when an interaction effect between CO\textsubscript{2} emissions and mean temperature was included, despite still not being significant, both variables became closer to being significant than when both pollution variables were included without the interaction effect. What may be occurring could be that the carbon-based aerosols have a net absorbing effect of radiation, further warming the atmosphere and surface (see Seto and Shepherd, 2009, p. 92).

Hale et al., (2006) analyzed how changes in LULC cover can influence temperature. The study found that after periods of the greatest LULC, 95% of the US Climate Normals stations located within a 10-km radius of the areas with the greatest LULC, experienced significant warming trends in minimum, maximum, and mean temperature. Argüeso et al., (2013) also analyzed future temperature projections in response to urbanization and concluded that urbanization will strongly affect minimum temperature, while having a minimal effect on maximum temperature (p. 2183).

Perhaps the patterns in Figure 9 suggest that many tornadoes are located downwind of urban areas. Results from Changnon (2001) found that storm enhancement occurs most frequently to the northeast, east, and southeast of cities with
populations of 1 to 2 million people, while larger cities such as New York and Chicago have the power to enhance and modify storms within the confines of the city. The downwind vs in-city enhancement results from the time it takes for urban influences to affect vertical motion and cloud microphysical processes (p. 163). If storm enhancement downwind of cities is replicated in other studies using various designs, areas such as Oklahoma, Arkansas, Mississippi, and Alabama ought to be the subject of future analyses.

Figure 9: A GIS image showing the number of tornadoes within each MSA. The amber color represents the various MSAs as defined by the US Census Bureau. Tornadoes with an Enhanced Fujita scale intensity of 0 are dark green. Light green depicts EF1 tornadoes; yellow depicts EF2 tornadoes, orange shows EF3 tornadoes, while red shows EF4 tornadoes. During 2010, an EF5 tornado was not recorded within the continental US.
Rozoff, Cotton, and Adegoke (2003) found that the Urban Heat Island plays the largest role in initiating deep moist convection downwind of the city. Convergence at the surface is enhanced on the leeward side of the city, while increased momentum drag over the city creates convergence on the windward side. The interaction of urban momentum drags and the UHI results in convection occurring downwind, as the momentum drag regulates the intensity of the UHI (p. 716). Similarly, Niyogi et al., (2011) found that urban regions were able to create distinct differences in regional convergence and convection patterns. The urban region of Indianapolis divided thunderstorm cells, but the cells merged further downwind of the urban center (p. 1141-1143).

Numerous observational studies support the claim that increasing urban surface roughness increases surface layer boundary convection. However, surface roughness was outside of the scope of this analysis. For this analysis, it was assumed that with urban sprawl, surface friction would increase as the natural landscape was transformed. This additional surface friction could be responsible for convection downwind of urban areas, signaling that both LULC and urban areas may work simultaneously to develop thunderstorms and tornadoes downwind. As LULC, surface roughness and urban sprawl seem to be related, Figure 10 visually plot the continental US land cover using the NLCD and suggests that tornado touchdown points coincide with land use transition zones. Figure 11 represents the NLCD Classification Legend (U.S. Department of Interior, n.d.).
Figure 10: A GIS image showing the number of tornadoes overlaying the land characteristics defined by the National Land Cover Database. Tornadoes with an Enhanced Fujita scale intensity of 0 are dark green. Light green depicts EF1 tornadoes; yellow depicts EF2 tornadoes, orange shows EF3 tornadoes, while red shows EF4 tornadoes. During 2010, an EF5 tornado was not recorded within the US.
Kellner and Niyogi (2014) found that in Indiana, regions of major LULC coincided with tornado touchdown points. As surface roughness decreased, there was also a decrease in the number of tornadoes that touched down. Their land use buffer analysis concluded that 61% of tornadoes that touched down in Indiana were within one km or urban land use, while 43% of tornadoes touched down within one km of forest land use (p. 28). Their results suggest that the distribution of tornado touchdown points indicate spatial relationships to urbanized areas, population density, topography, and how land use is classified. Pryor and Kurzhal (1997) suggest an apparent trend in tornado touchdown points from 1950 to 1995, where tornadoes touched down in counties with lower population densities, and higher surface roughness (p. 525-526).

What is missing from the analysis is any account for the topographic changes in the urban landscape or surface moisture sources such as rivers and lakes and how
and to what extent they impact tornado genesis. Yet, it is widely known that the actions of humans are the most powerful factor rearranging the surface of the earth, much more powerful than the impact of natural processes such as water, wind, temperature, volcanic eruptions, tsunamis and earthquakes. In Minnesota alone, Schoeneberger (2002) found a clear relationship between terrain features and tornado touchdown points, specifically of rivers with a W-E or SW-NE axis. The slope of the river valley acts as a funnel while weakening the disruption of low-level airflow. These results correspond well to what Figure 73 shows for Minnesota during 2010, suggesting that spatial recognition analysis may be more meaningful at a local level, rather than at regional or national levels.

10.5 Research Caveats and Data Biases

Despite this speculative analysis laying the groundwork for future research into the role that human pollution plays in tornado and thunderstorm development, this analysis is not without a few caveats. These caveats need to be improved in future work in order to make more substantial claims linking pollution with tornado occurrence and development. One of the biggest caveats within the methodology used derived from the EPA pollution dataset. Over the last few decades, pollution monitoring stations have been commissioned and decommissioned for various reasons. Some existing pollution datasets cover a few years, while others are for sporadic periods in time. Given the spotty nature of pollution monitoring stations across the continental US, ozone was the only pollutant that was available for all 40 MSAs during 2010. It is probably not the best measurement. The availability of other measures of pollution would have allowed us to conclude more confidently whether a certain type of pollutant helps aid in tornado development. Likewise, this analysis was
forced to extrapolate the pollution data to span the entire MSA boundary, for it was very difficult to determine the exact location of the pollution monitoring stations within the MSA boundary. The pollution monitoring stations represented one specific point in time and space and had to be extrapolated to represent the pollution levels across the entire MSA. The result is that it was impossible to account for the dynamic pollution level fluctuations varying by space and time. The research would have been more comprehensive if it was able to include more than one pollution variable. Carbon dioxide emissions were also included in the analysis. In 2010, site specific facilities could report their carbon dioxide emissions voluntarily, for they were not required to do it. During 2010, carbon dioxide monitoring was in its infancy stages, and the data reporting was subpar at best. The sites that did report their emissions were summed together to represent the carbon dioxide emissions within the MSA boundaries. The EPA did break down the carbon dioxide emissions into subcategories such as transportation, manufacturing, power generation. However, the data was only partial, for each MSA did not have a site-specific emissions report for each category of pollutants.

Many of the regression models used for this study found increases in population to be a statistically significant predictor of increases in pollution (not shown). However, it would be ill-advised to conclude that the number of tornadoes have in fact increased since 1951 on the basis of the information collected in 2010, the year used in this study. To date, the best and most complete tornado dataset for investigating tornado climatology comes from the SPC spanning from 1950 to the present (Farney and Dixon, 2015, p. 2993). Initial examination of the SPC dataset reveals an increasing trend in the overall number of tornadoes reported over time,
from about 600 per year at the onset of the dataset to about two and a half times that value more recently (Farney and Dixon, 2015; Coleman and Dixon, 2014). Without additional analyses of raw tornado data, it would be appropriate to conclude that tornado occurrences have been trending positively since 1950. An additional question of whether the increase in tornado reports corresponds to systematic biases such as meteorological and non-meteorological factors is subject to future research.

The history of certifying and validating official tornado reports within the US is relatively brief compared to other meteorological phenomena but contain significant changes to the overall collection process that should be noted (Widen, Fricker, and Elsner, 2015, p. 157). The initial task of collecting tornado reports began in 1916 with the United States Weather Bureau issuing public tornado forecasts beginning in 1952 (Widen, Fricker, and Elsner, 2015; Galway, 1977). The Tornado Watch and Warning program implemented in 1953 also included a network of tornado spotters (Widen, Fricker, and Elsner, 2015; Galway, 1977). The National Weather Service adopted The Fujita Scale (F-Scale) during the late 1970s to evaluate tornado intensity based on damage severity (Widen, Fricker, and Elsner, 2015; McCarthy, Schaefer, and Edwards 2006). In an attempt to add additional raw data to the tornado dataset, earlier tornadoes were retroactively rated based upon newspaper articles and photographs. Some of these newspaper articles may have contributed to exaggeration and overrating of some tornado occurrences (Widen, Fricker, and Elsner, 2015; Schaefer and Edwards, 1999; Verbout et al., 2006).

Anderson et al., (2007) argues that despite best efforts to maintain the integrity and homogeneity of the SPC’s tornado dataset, the dataset is unintentionally corrupt with non-meteorological influences (p. 571). Some of these influences reside with
inconsistent reporting standards, tornadoes going unreported, and the reports of some fictitious tornadoes (Forbes and Wakimoto 1983; Doswell and Burgess, 1988). Given that these non-meteorological influences contribute to the primary cause for spatial and temporal variability for tornado reporting, the exact number of United States tornado occurrences remains an unknowable quantity (Anderson et al., 2007; Schaefer and Galway, 1982; Grazulis and Abbey 1983; Brooks, Lee, and Craven, 2003).

Beginning in 1989, The National Weather Service began an initiative to confirm tornado warnings more efficiently, resulting in a substantial increase of F0 tornadoes. A few years later, the WSR-88D weather radar was installed across the country, further increasing the number of F0 tornadoes reported (Farney and Dixon, 2015; Doswell, 2007). The increase in reported tornadoes attributes to better public awareness of tornadoes, precisely due to better media coverage and available information on the internet. Additionally, the increased presence of tornado chasers has also helped increase the number of tornadoes reported (Farney and Dixon, 2015; McCarthy and Schaefer, 2004). On the other hand, researchers have also reported that tornadoes have gone both unreported or unwitnessed (Farney and Dixon, 2015; Elsner et al., 2013). Anderson et al., (2007) found regional variability in tornado reports regarding suburban and rural areas of the Great Plains. The authors attributed this variability to obstruction factors such as trees and vegetation, the absence of roads and highways, and the population density. Likewise, the study also referenced demographic factors such as infrastructure quality, rural construction density, varying reporting standards, all of which could contribute to variability in the population bias at a regional level (p. 572-573).
The population bias has become well known and widely reported within research studies (Elsner et al., 2013; Snider, 1977; Doswell et al., 1999). Anderson et al. (2007) note that previous research has modeled population using either county population density or the population density of rural areas. Research using county population density can inherit bias from cities and large towns being present. The county population density may not accurately portray the representativeness of man-made infrastructure and the density of humans within rural areas (p. 572). Over time this could potentially introduce a significant bias where tornado reports outside of urban areas tend to be less numerous (Elsner et al., 2013, p. 221).

Ray et al., (2003) note that tornado touchdown occurrences tend to maximize near National Weather Service radars and population centers (p. 1026). Additional studies also recognize the population bias within the tornado dataset (Schaefer and Galway, 1982; Grazulis and Abbey, 1983). However, in some outlier situations, it is not possible to consistently correlate population centers with tornado touchdown points (Grazulis and Abbey, 1983; King 1997). Anderson et al., (2007) evaluated the population bias for regions surrounding several large urban areas in the central and eastern US and found the bias to have regional variability (p. 577). Using a hierarchical Bayesian model to correct for the population density bias, the authors were able to conclude that F2-F5 tornadoes were affected less by the population bias as were F0-F1 tornadoes. This finding held true for Atlanta, Georgia, Champaign, Illinois, and Des Moines, Iowa, but the results were opposite for Oklahoma. One explanation was due to the misclassification of several F0-F1 tornadoes, which were worthy of F2-F5 status (Anderson et al., 2007, p. 571).
Elsner et al., (2013) found that over the history of the SPC tornado dataset, the number of reported tornadoes across the areas prime for storm chasing within the Great Plains had the lowest tornado reports in the countryside. The reported tornadoes in the countryside had increased since the 1970s but had the most dramatic increase since 1996. On the other hand, the study concluded that the tornado report density between the countryside and the urban areas was statistically indistinguishable between 2002 and 2011. The study also concluded that the population bias on average was less pronounced for tornadoes rated F0 while disappearing more quickly over time for F1-F5 tornadoes (p. 229).

Non-meteorological factors may only partially explain some of the noise within the dataset. Researchers continue to understand the role meteorological factors play in biasing the overall representativeness of the tornado dataset. Elsner and Widen, (2014) examined the spatial and temporal variability in the efficiency of tornado days since 1954, and found that after removing F0 tornadoes from analysis, there was considerable yearly fluctuation, but no long-term trend. However, the authors concluded that the number of tornado days has been decreasing since 1970 given that the atmosphere was producing more tornadoes on less days (p. 259). Said another way, there are fewer tornado days overall, but on days were tornadoes do form, there are more of them (Widen, Fricker, and Elsner, 2015, p. 159). Elsner and Widen, (2014) also looked at analyzing daily tornado counts and found that daily US tornado counts follow a power-law relationship regarding frequency distribution. Mostly, the daily number of tornadoes in the other damage category, on average, is about twice that of the current category (p. 259). This power-law relationship also appears with the
length and number of consecutive tornado days (Farney and Dixon, 2015, p. 2993-2995).

Recently, it has become possible to estimate individual tornadic energy using the SPC’s tornado dataset and building upon Fricker, Elsner, Camp, and Jagger (2014). According to Widen, Fricker, and Elsner (2015) comparing tornadoes based on kinetic energy assumes the highest intensity of a tornado based upon the tornado’s path length and width along with accounting for the spatial distribution of winds by damage rating. Applying this method to the most recent set of tornadoes within the dataset since 2007, the authors concluded that 2011 distinctly stood out as the most energetic tornado season over the last seven years. Using energy estimates as a basis for comparison, individual tornado comparisons could be made between tornadoes that go well beyond historical intensity ratings (p. 163).

Whether meteorological or non-meteorological factors play more of a significant role masking the actual representativeness of the overall tornado dataset, is beside the point, for this analysis does not account for the yearly fluctuations of tornado touchdowns, let alone any other large-scale atmospheric circulation patterns that may influence tornado touchdowns from year to year. 2010 may be either more or less active than an average year, and further investigative work can help determine if this is the case. However, the logical questions it poses are entirely immune to these other issues having to do with the identification of these storms.
Chapter 11
SUMMARY AND CONCLUSIONS

According to the IPCC, researchers have been able to report with more confidence that the frequency of heavy rainfall and intensity of heat waves have increased, the areas directly affected by heat waves have also increased in many regions, and that tropical cyclone activity in the North Atlantic Ocean has also increased (IPCC, 2007; Bouwer, 2011). While at much lower levels of aggregation, results from this study shows that the urban landscape plays an increasingly important role in thunderstorm and tornado development. As population continues to grow, people have become increasingly reliant on specific dimensions of the natural environment to provide the resources they need. This never-ending dependence is coming at the expense of nature.

What were once considered lush and green vegetative landscapes are now giving way to highways, skyscrapers, and urban infrastructure, and this drastic pattern has also begun to shift our understanding of how energy and moisture flow through the natural environment. In the urban areas, artificial infrastructures act as heat sinks during the day, trapping large amounts of radiation and heat during the day, to slowly release it during the night. The impact of this heat sink is to create a large heat plume known as the UHI, which is responsible for large temperature gradients when compared to rural surroundings; moisture levels are lower in these urban areas, while pollution levels are much higher.

Research in this study (not shown) indicated that urban O₃ concentrations might correlate and potentially impact the spatial distribution of tornado touchdowns during the year of 2010. Very densely populated and compact cities exhibited lower
O₃ concentrations, while less densely populated and more sprawling cities had higher O₃ concentrations. This trend held true for areas was across the southeast, and lower Midwest, where the highest number of tornado touchdowns occurred. These geographical regions were also responsible for some of the largest LULC transitions caused by large sprawling populations.

This study was unable to determine whether or not the UHI played a direct role in spawning tornadoes by temperature gradient alone. The assumption was that increasing pollution levels within urban areas would increase temperatures due to the radiation properties of ozone and CO₂ particles. However, given that temperature played an insignificant role in explaining the geographic distribution of tornado touchdowns, urban areas must alter thunderstorm and tornado development in other ways not explored in this study. Rather than temperature and pollution alone, surface roughness and friction within the Planetary Boundary Layer (PBL) may play a more significant role in surface convergence. Since this study did not account for the effects of topography and large bodies of water on tornado development, in future studies those two factors may provide valuable insight into predicting the geographic distribution of tornados. Regardless, O₃ concentrations were preliminarily found to play a more symbolic role in better understanding the geographical distribution of tornado touchdowns.

Despite this research accounting for only 2010, it provides an additional narrative to the growing body of knowledge attempting to correlate the ingredients of risk and exposure with the increasing built-environment, specifically the tornado risk landscape. At the very least, this research portrays a critical finding that the elevated risk for tornado disaster potential is neither temporally nor spatially bound. Given the
considerable variability in both footprint risk and tornado exposure, the expanding bulls-eye effect and acceleration of urban development will continue to pave the way for frequently higher impact from tornado hazards (Ashley and Strader, 2016, p. 782). Large regions outside of urban centers are becoming exurban and suburban, inferring that more people and housing units are residing in the direct path of severe weather (Rosencrants and Ashley, 2015, p. 136). Many of the geographic areas identified in this study present a supplemental part of the United States where the highest risk for tornadoes exists. These areas, similar to the areas outlined in Coleman and Dixon (2014), are distinctly different from the areas within tornado alley, that many people are uninformed about the risk for tornadoes outside of tornado alley.

Over the last few years, climate researchers have begun the process of revealing the potential for more frequent and more variable environments that are conducive for severe convective thunderstorms and their associated hazards resulting from anthropogenic climate change. However, recent findings insinuate that tornado disaster trends, associated impacts, and their potential are an amalgamation of changes in both vulnerability and risk landscapes (Ashley and Strader, 2016, p. 767). Given the intricacy of disaster attribution, limited research exists which assesses the interrelationship of disaster driving factors in an integrated framework (Huggel, Stone, Auffhammer, and Hansen, 2013, p. 694). Rather, the current body of literature concentrates on climatological risk or human and physical vulnerabilities in isolation of each other (Ashley and Strader, 2016, p. 767). At the very least, this research builds upon the common narrative that the growing impacts resulting from disasters are primarily driven by escalating development and exposure.
Sustainable development supports fundamental societal and systems transitions and transformations that limit global warming. The IPCC states with high confidence that many synergies exist between sustainable development and adaptation options that reduce the vulnerability of human and natural systems. If managed appropriately, these synergies can be used to help reduce society’s overall risk to various disasters. In order to improve overall resiliency and the overall adaptive capacity of society, increased investments in physical and social infrastructure are both key-enabling conditions. “Climate change impacts and responses are closely linked to sustainable development which balances social well-being, economic prosperity and environmental protection (IPCC, 2018).”

In sum, this research was motivated by the possible presence of complex system dynamics in which Newtonian reasoning guiding a well-understood system, as is the case here, is only partially accurate. Wind, earth, water, and fire have an immense ability to drastically alter the natural landscape, representing the natural aspect to disasters, but the effects caused by human action is paramount. Disasters are becoming more complex over time while encompassing all aspects of society. There may be a recursive process going on, in which the efforts to build more massive and resistant buildings to guard against tornadic storms, as is done today, may in fact have the opposite effect intended. Artificial infrastructure and development may be playing a more indirect role regarding tornado touchdown points, an example of an unexpected mechanism property of complex system dynamics. As human life form continues to dominate and shape the planet, we must remain vigilant about how our current actions affect the future in unplanned and unforeseen ways. Mankind, whether it be for good or for bad, will remain the largest driver of change in nature.
11.1 Future Research

This analysis has continued to explore the intersection between the physical environment and human life form, specifically man’s ingenuity and cataclysmic power of morphing the natural environment. This research relied heavily on some data biases but was able to put forth a working hypothesis suggesting that metropolitan statistical areas may play a role in influencing one or more of the physical mechanisms responsible for thunderstorm and tornado environments. Given that this research was unable to establish a direct link between MSAs and tornado frequency, the results from this study further the discussion that disasters have become multifaceted and require a multidisciplinary approach to better understand them. At the very least, this comprehensive study illustrates a thorough and comprehensive review of the available literature, providing a road map of additional avenues for future research.

In the future, it would be worthwhile to have included more than 40 MSAs within the analysis. The analysis chose 40 MSAs based upon pollution availability, with several MSAs being located west of the Rocky Mountains; an area unfavorable for significant tornado touchdowns. It would be worthwhile to use all 349 MSAs identified by the US Census, or to focus solely on the MSAs within tornado alley. Either have the MSAs within a specific geographical location, or to focus on the topographical effects on thunderstorm and tornado development. Mountains, valleys, and large water bodies, all have the capability of disrupting the natural air flow into a thunderstorm cell.

Another avenue of future research would be to include a temporal or diachronic analysis accounting for yearly fluctuations in tornadoes and tornado touchdown points, rather than using a single year. This thesis only addressed one point in time and could not adequately conclude whether the MSA itself played a larger role
in tornado development or if instead large-scale atmospheric conditions were responsible. Having multiple years included within the analysis would have helped provide more insight into which factor played a more significant role. Having multiple years would also provide more insight into the pollution trends as well. Pollution levels before and after 2010 would have shown if pollution levels were trending in a positive direction and their relationship to the occurrence of tornadoes.

It would be highly recommended having more cities in the analysis, for this research used only 40 MSAs and five independent variables. Increasing the number of MSAs would allow the use of the standard criteria of statistical significance and thus increase the dependability of the findings such as the effect of pollution on thunderstorm and tornado development. Furthermore, the analysis would be more comprehensive if it were able to account for the aerodynamic effect and surface roughness properties of the urban landscape, as well as clarify how in a warmer climate, CAPE values and wind shear change, to test if wind shear would decrease while CAPE increases. Tornadoes need both ingredients to form.

Additionally, rather than having one pollution monitoring station represent the entire MSA boundary, a more comprehensive pollution dataset should be used. Having multiple pollution monitoring stations would allow for a more granular analysis regarding where the tornado touchdown point was with respect to the pollution monitoring station and the MSA center. More granular pollution data could also help establish a cause-effect relationship between the two variables while providing insight into where this interaction occurs, whether it be on the windward or leeward side of the MSA center. This analysis was unable to account for any association or predictive tests that occurred on the leeward side of the MSA center, other than noting that the
tornado touchdown point occurred downwind of the MSA center. One way to account for any interaction on the leeward side of an MSA would be to only count the number of tornadoes that occurred within an MSA boundary, but downwind of the MSA center.

One final hope is for future studies to generate a more valid way of accounting for CO$_2$ emissions. The analysis used a very crude dataset provided by the EPA in order to account for carbon dioxide at the MSA level. Having a more comprehensive way of accounting for the increase in carbon emissions would help to strengthen the test of the theoretical framework guiding this hypothesis. The current EPA carbon dioxide dataset is still in its infancy stage. Only time will tell how the reliability of carbon dioxide monitoring dataset will be shaped in the future.
REFERENCES


Figure A.1: Scale definitions along with the time and horizontal scale characteristics of a variety of atmospheric processes (American Meteorological Society, 2012a).

Figure A.2: Buoyancy of a rising air parcel because of condensation and the release of heat into the environment (Nisley, 2014).
Figure A.3: The three stages of thunderstorm development which include the developing stage, mature stage, and dissipating stage (Ahrens, 1994).

Figure A.4: Many of the features associated with a supercell (Colorado State University, 2015).
Figure A.5: The process of vortex stretching and the “Dynamic Pipe Effect” (Colorado State University, 2015).

Figure A.6: The “Bottom Up” formation of tornadoes (Colorado State University, 2015).
Figure A.7: The role shear and tilting play in forming tornadoes (Colorado State University, 2015).

Figure A.8: The average annual number of tornadoes per state between the years from 1991-2010 (NCEI, n.d.).
Figure A.9: Yearly tornado average per 10,000 square miles (Midwestern Regional Climate Center, 2014).

Figure A.10: Tornado probability of occurrence during May between the years of 1982-2011 (NCEI, n.d.).
Figure A.11: Tornado probability of occurrence during June between the years of 1982–2011 (NCEI, n.d.).

Figure A.12: Tornado probability of occurrence during September between the years of 1982–2011 (NCEI, n.d.).
Figure A.13: Tornado probability of occurrence during November between the years of 1982–2011 (NCEI, n.d.).

Figure A.14: Geographical boundaries of “Tornado Alley” (Concannon, Brooks, and Doswell III, 2000; NCEI, n.d.).
Figure A.15: Geographical location of “Dixie Alley” shown using mean number of tornado days (NCEI, n.d.).

Figure A.16: Time of day for “Tornado Alley” when tornadoes occur. The graph uses military time and is between the years of 1950–2010 (NCEI, n.d.).
Figure A.17: Time of day in “Dixie Alley” when tornadoes occur. The graph uses military time and is between the years of 1950-2010 (NCEI, n.d.).

Figure A.18: Time of day over the entire US when tornadoes occur. The graph uses military time and is between the years of 1950–2010 (NCEI, n.d.).
Figure A.19: The three-different urban land use descriptive models (Changing Cities, n.d.).
Figure A.20: A map, showing high-resolution housing density across the entire country in (a) 1980; (b) 1990; (c) 2000; (d) 2010; (e) 2020; and (f) 2030. The dark red shade corresponds to an urban density; orange is a suburban density, yellow is an exurban density, green is a rural density, while gray is undeveloped (Theobald, 2005, p. 14-15).
Figure A.21: A map is showing the proportion of the country that is rural compared to urban in 1980. The higher the percentage, the darker the shade of green is, which symbolizes rural high areas. The lower the percentage the more urbanized the land is, with the colors changing to red and orange (Theobald, 2005, p. 15-18).

Figure A.22: A map showing the proportion of the country that is rural compared to urban in 2000. The higher the percentage, the darker the shade of green is, which symbolizes rural high areas. The lower the percentage the more urbanized the land is, with the colors changing to red and orange (Theobald, 2005, p. 15-18).
Figure A.23: A map showing the proportion of the country that is rural compared to urban in 2020. The higher the percentage, the darker the shade of green is, which symbolizes rural high areas. The lower the percentage the more urbanized the land is, with the colors changing to red and orange (Theobald, 2005, p. 15-18).
Figure A.24: Maps of change in population density, exurban land use, and cropland use in the United States from 1950 until 2000 (Brown, Johnson, Loveland, and Theobald, 2005, p. 1857).
Figure A.25: NLCD geospatial analysis of the distribution and magnitude of land cover change for the continental United States between 2001 and 2011 (Homer et al., 2015, p. 352).

Figure A.26: This framework shows how the urban ecosystem (lower right) is a driver of (upward arrows) and responder to (downward and horizontal arrows) environmental change. Changes in biogeochemical cycles, climate, hydro systems, and biodiversity result from land change to build cities (Grimm et al., 2008, p. 758).
Figure A.27: A histogram showing significant trends in minimum (top) and maximum (bottom) temperature anomalies for before and after stations respective periods of significant LULC change (Hale et al., 2006, p. 3).
Figure A.28: Comparison of the six common pollutants measured by the EPA nationwide from 1990-2010 (Our Nation’s Air, 2012, p.1).
Figure A.29: The overall distribution of total emission estimates nationwide by source category for specified pollutants in 2010 (Our Nation’s Air, 2012, p. 4).

Figure A.30: Number of people living in counties with air quality concentrations above the threshold levels of the National Ambient Air Quality Standards in 2010 (Our Nation’s Air, 2012, p.6).
Figure A.31: Shows the National 8-hour ozone level trend from 2001-2010 (Our Nation’s Air, 2012, p. 9).

Figure A.32: National PM$_{2.5}$ trends between 2010 and 2010 (Our Nation’s Air, 2012, p. 12).
Figure A.33: National PM$_{10}$ concentrations between 2001 and 2010 (Our Nation’s Air, 2012, p. 15).

Figure A.34: National US lead concentrations from 2001 until 2010 (Our Nation’s Air, 2012, p. 16).
Figure A.35: NO$_2$ national concentration levels between the years of 2001 and 2010 (Our Nation’s Air, 2012, p. 17).

Figure A.36: National CO trend between 2001 and 2010 (Our Nation’s Air, 2012, p. 17).
Figure A.37: SO$_2$ national concentrations between the years of 2001 and 2010 (Our Nation’s Air, 2012, p. 17).

Figure A.38: Path of pollution particles within the atmosphere (Mayer, 1999, p. 4031).
Figure A.39: Comparison of US economic growth measures and pollution emissions between the years of 1998-2008. The Carbon dioxide emissions are between the years of 1990 and 2007 (Our Nation’s Air, 2012, p. 5).

Figure A.40: Near the surface atmospheric CO₂ concentrations averaged over a 24-hour period along the transect (rural, suburban, and urban sites) for the 5 years of the study (George et al., 2007, p. 7654).
Figure A.41: Representation of the physical processes regarding the urban microclimate and air pollution (Hidalgo, Masson, Baklanov, Pigeon, and Gimeno, 2008, p. 355).

Figure A.42: Detailed breakdown of the various greenhouse gas emissions by sector per year (IPCC, 2007, p. 3).
Figure A.43: Relationship between population and pollution varying by region (Hansen, 2013).
Figure A.44: Estimates of the global radiative forcing (W/m²) that result from changes in key-climate related air particles on a global basis between the pre-industrial era and 2005 (Forster et al., 2007, p. 131-132).

Table A.1: The various ways urban land-use changes, urban aerosols, and anthropogenic greenhouse gases affect the climate system (Hidalgo et al., 2008, p. 355).

<table>
<thead>
<tr>
<th>Various pathways for urbanization to impact the climate system (see text for references)</th>
<th>Urban land-cover</th>
<th>Urban aerosols</th>
<th>Anthropogenic greenhouse gas (GHG) emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban heat island and mean surface temperature record</td>
<td>Surface energy budget</td>
<td>Insolation, direct aerosol effect</td>
<td>Radiative warming and feedbacks</td>
</tr>
<tr>
<td>Wind flow and turbulence</td>
<td>Surface energy budget, urban morphological parameters, mechanical turbulence, bifurcated flow</td>
<td>Direct and indirect aerosol effects and related dynamic/thermodynamic response</td>
<td>Radiative warming and feedbacks</td>
</tr>
<tr>
<td>Clouds and precipitation</td>
<td>Surface energy budget, UHI destabilization, UHI meso-circulations, UHI-induced convergence zones</td>
<td>Aerosol indirect effects on cloud-precipitation microphysics, insolation effects</td>
<td>Radiative warming and feedbacks</td>
</tr>
<tr>
<td>Land surface hydrology</td>
<td>Surface runoff, reduced infiltration, less evapotranspiration</td>
<td>Aerosol indirect effects on cloud-microphysical and precipitation processes</td>
<td>Radiative warming and feedbacks</td>
</tr>
<tr>
<td>Carbon cycle</td>
<td>Replacement of high net primary productivity (NPP) land with impervious surfcon</td>
<td>Black carbon aerosols</td>
<td>Radiative warming and feedbacks, fluxes of carbon dioxide</td>
</tr>
<tr>
<td>Nitrogen cycle</td>
<td>Combustion, fertilization, sewage release, and runoff</td>
<td>Acid rain, nitrates</td>
<td>Radiative warming and feedback, NOx emissions</td>
</tr>
</tbody>
</table>
Figure A.45: The panel shows the evolution of deep convection in a pristine environment while the bottom panel shows deep convection in a polluted environment. In the pristine environment, rain droplets coalesce into larger rain drops before raining out. In the polluted environment, the smaller droplets do not precipitate before reaching supercooled levels, where they freeze into ice particles, that melt as they fall towards lower levels. Additional latent heat released from freezing aloft and reabsorbed heat at lower levels from melting, implies a greater upward transport of heat. This results in more vigorous convection and additional rainfall, despite a slower cloud to rain droplet conversion (Rosenfeld et al., 2008, p. 1309-1310).
Figure A.46: The various research studies pertaining to the effects of aerosols on precipitation and precipitation particle size (Khain, 2009, p. 13).
Figure A.47: Decadal trends of the maximum temperature averaged for every US station below an elevation of 500m. Each value (in °C per decade) was calculated from the average of the 1990s minus the 1980s and the 1970s minus the 1960s maximum temperatures. The average value of the trend is indicated by the side panel with (a) station (observed) maximum temperature trends (b) NNR (analyzed) maximum temperature trends (c) observed minus analyzed maximum temperature trends (Kalnay and Cai, 2003, p. 529-530).
Figure A.48: Decadal trends for minimum temperatures averaged for every U.S. station below the elevation of 500m (Kalnay and Cai, 2003, p. 529-530).
Table A.2: The basic characteristics of surface and atmospheric urban heat islands (UHIs) (U.S. Environmental Protection Agency, 2008).

<table>
<thead>
<tr>
<th>Feature</th>
<th>Surface UHI</th>
<th>Atmospheric UHI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temporal Development</td>
<td>Present at all times of the day and night</td>
<td>May be small or non-existent during the day</td>
</tr>
<tr>
<td></td>
<td>Most intense during the day and in the summer</td>
<td>Most intense at night or predawn and in the winter</td>
</tr>
</tbody>
</table>
| Peak Intensity (Most intense UHI conditions) | More spatial and temporal variation:  
  • Day: 18 to 27°F (10 to 15°C)  
  • Night: 9 to 19°F (5 to 10°C) | Less variation:  
  • Day: -1.8 to 5.4°F (-1 to 3°C)  
  • Night: 12.6 to 21.6°F (7 to 12°C) |
| Typical identification Method | Indirect measurement:  
  • Remote sensing | Direct measurement:  
  • Fixed weather stations  
  • Mobile traverses |
| Typical Depiction            | Thermal image                                                                | Isotherm map                                                                     |
|                             |                                                                               | Temperature graph                                                                |

Figure A.49: A figure that shows how average annual temperatures have changed in various parts of the country since the early 20th century (Since 1901 for the contiguous 48 states, and 1925 for Alaska) (Climate Change and Heat Islands, n.d.).
Figure A.50: This figure shows how the surface and atmospheric temperatures vary over different land use areas. The surface temperatures vary more during the daytime compared to the nighttime where they are similar (Heat Island Effect, n.d.).

Figure A.51: This figure depicts a highly developed urban area (left) which is characterized by 75-100 percent impervious surfaces, which have less moisture available for evapotranspiration than a natural ground cover, which has less than 10 percent impervious cover (right). This characteristic contributes to a higher surface and air temperature for corresponding urban areas (U.S. Environmental Protection Agency, 2008).
Figure A.52: Conceptual depiction of the diurnal evolution of the urban heat island during calm and clear conditions. Atmospheric urban heat islands primarily result from different cooling rates between urban areas and their surrounding rural or non-urban surroundings (a). The heat island intensity (b) typically grows from mid-to-late afternoon to a maximum a few hours after sunset (U.S. Environmental Protection Agency, 2008).
Figure A.53: The response of the ensemble-mean number of days with severe thunderstorm environments (NDSEV) in the late 21st century during winter (DJF), spring (MAM), summer (JJA), and autumn (SON). This climate model assumes an elevated greenhouse gas emissions scenario (Diffenbaugh, Scherer, and Trapp, 2013, p. 16362).
Figure A.54: The future response of CAPE and wind shear in the late 21st century during the winter (DJF), spring (MAM), summer (JJA), and autumn (SON) using an elevated greenhouse gas emissions scenario. The left-hand side are the differences in CAPE with the right-hand side showing the magnitude of the vector difference of the 6km horizontal wind (Diffenbaugh, Scherer, and Trapp, 2013, p. 16361-16363).
Figure A.55: A time series of the yearly tornado report (blue solid line), days tornadoes occurred (red solid line), Fujita scale F2-F5 tornado reports (green solid line), and population (black dotted line) (Diffenbaugh, Trapp, and Brooks, 2008, p 554).

Figure A.56: The US population change from 1950 to 2010 (Mackun et al., 2012, p. 1-2).
Figure A.57: The US Census regions and corresponding states (Mackun et al., 2011, p. 3).
Table A.3: The population change for the entire US, each state, and by each region, including Puerto Rico from 2000 to 2010 (Mackun et al., 2011, p.3).

<table>
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<tr>
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<td><strong>Puerto Rico</strong></td>
<td>3,809,810</td>
<td>3,725,789</td>
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</tbody>
</table>
Table A.4: Population by Core Statistical Area (CBSA) for 2000 and 2010 (Mackun et al., 2011, p. 4).

**Population by Core Based Statistical Area (CBSA) Status: 2000 and 2010**

(For information on confidentiality protection, nonsampling error, and definitions, see [www.census.gov/prod/2014pubs/acs-171.pdf](http://www.census.gov/prod/2014pubs/acs-171.pdf))

<table>
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<tr>
<th>Area</th>
<th>Population</th>
<th>Share of U.S. population</th>
<th>Change</th>
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<td>2010</td>
<td>2000</td>
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<td>United States</td>
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<td>Inside CBSA</td>
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<td>Micropolitan</td>
<td>29,220,400</td>
<td>30,943,552</td>
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<td>Outside CBSA</td>
<td>19,131,679</td>
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</table>

Note: Metropolitan and micropolitan statistical areas defined by the Office of Management and Budget as of December 2009. Broomfield County, CO, was formed from parts of Adams, Boulder, Jefferson, and Weld Counties, CO, on November 15, 2001, and was coextensive with Broomfield city. For purposes of presenting data for metropolitan and micropolitan statistical areas, Broomfield is treated as if it were a county at the time of Census 2000.

Figure A.58: Population change as a percentage across the US for metropolitan and micropolitan statistical areas from 2000 until 2010 (Mackun et al., 2011, p. 5).
Figure A.59: Population numeric and percentage changes by county from 2000 until 2010 (Mackun et al., 2011, p. 7).
Figure A.60: Population distribution for each county in the US for 2010 (Mackun et al., 2011, p. 8).

Figure A.61: County Population density for the US, for 2010 (Mackun et al., 2011, p. 10).
Appendix B

ACRONYMS

%ISA – Percent Impervious Surface
AGL – Above Ground Level
AM – April - May
AMJ – April, May, June
AprilSeptO₃ – April to September Ozone
AprilSeptTemp – April to September Temperature
AQS – Air Quality System
ARPS – Non-Linear Numerical Model
ASOS – Automated Surface Observing Station
CAPE – Convective Available Potential Energy
CBD – Central Business District
CBSA – Core Based Statistical Area
CCN – Cloud Condensation Nuclei
CH₄ – Methane
CMIP5 – Coupled Model Intercomparison Project, Phase 5
CO – Carbon Monoxide
CO₂ – Carbon Dioxide
CO₂E – Carbon Dioxide Equivalent
COAMPS – Coupled Ocean/Atmospheric Mesoscale Prediction System
DJF – December, January, February
DTA – Dixie Tornado Alley
DTR – Diurnal Temperature Range
EHE – Extreme Heat Event
ENSO – El Niño Southern Oscillation
EOF – Empirical Orthogonal Function
EPA – Environmental Protection Agency
ETM+ - Enhanced Thematic Mapper Plus
GCM – Global Circulation Model
GDP – Gross Domestic Product
GEM – Canopy Resistance Scheme Using Photosynthesis
GHCN-M - Global Historical Climatology Network Monthly
GHG – Greenhouse Gases
GHGRP – Greenhouse Gas Reporting Program
GISS – Goddard Institute for Space Studies
HadCRUH – Hadley Center and Climate Research Unit Global Surface
HC – Hydrocarbons
HCR – Horizontal Convective Rolls
IPCC – Intergovernmental Panel on Climate Change
IPCC A2 – Intergovernmental Panel on Climate Change A2 Emission Scenario
JJA – June, July, August
LCL – Lifting Condensation Level
LFC – Level of Free Convection
Log CO₂ – Log Base 10 Carbon Dioxide
LST – Land Surface Temperature
LTER – Long Term Ecological Research
LULC – Land Use/Land Cover
LUTRAQ – Land Use, Transportation, and Air Quality
MAM – March, April, May
MCS – Mesoscale Convective System
METROMEX – Metropolitan Meteorological Experiment
MSA – Metropolitan Statistical Area
N₂O – Nitrous Oxides
NAAQS – National Ambient Air Quality Standards
NALLJ – North American Low-Level Jet
NASA – National Aeronautics Space Administration
NDSEV – Number of Days With Severe Thunderstorm Environments
NDVI – Normalized Difference Vegetation Index
NLCD – National Land Cover Database
NNR – NCEP/NCAR 50-Year Reanalysis
NO₂ – Nitrogen Dioxide
NOAA – National Oceanic Atmospheric Administration
NOUCP – Simpler Urban Canopy Parameterization of Roughness, Albedo,
NSSFC – National Severe Storms Forecast Center
O₃ – Ozone
OLS – Operational Linescan System
PB – Lead
PBL – Planetary Boundary Layer
PGF – Pressure Gradient Force
PM – Particulate Matter
PPB – Parts Per Billion
PPM – Parts Per Million
PTA – Plains Tornado Alley
RAMS – Regional Atmospheric Modeling System
SO₂ – Sulfur Dioxide
SODAR – Sound Detection and Ranging
SON – September, October, November
SQRTPop – Square Root of Population
SST – Sea Surface Temperatures
TCMA – Twin Cities Metropolitan Area
TEB – Town Energy Budget
TM – Thematic Mapping
TNI – Trans-Niño Index
UA – Urban Area
UHI – Urban Heat Island
URE – Urban Rainfall Effect
USHCN – U.S. Historical Climatology Network
VMT – Vehicle Miles Traveled
VOC – Volatile Organic Compound
WRF – Weather and Research Forecast
WRF-CHEM – Weather Research and Forecasting Chemistry
WSR-88D – Weather Surveillance Radar, 1988, Doppler